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ELIHU THOMSON

Presented with the Kelvin Medal for 1923, at London, July 10, 1924

The principal British and American Engineering Societies united in recommending him for this award granted triennially as a mark of distinction for engineering work or investigation of the kinds with which Lord Kelvin was especially identified. Professor Thomson's long and productive work has resulted in many notable achievements in electrical invention, electrical and mechanical engineering, industrial development, and scientific research

GENERAL ELECTRIC
REVIEW

PRIZES, FAMILIARITY AND THE PUBLIC

This summer we followed with enthusiasm the reports of the Olympic Games in France and rejoiced in the succession of prizes won by the American delegation of athletes. One evening a short time ago our attention centered upon a musical contest held at the Lewisohn Stadium, New York City, and broadcast by radio as a special feature of this season's Symphony Concerts of the New York Philharmonic Orchestra. Two elements served to whet our interest in this event: without bestirring ourselves from our homes we occupied "grandstand seats," and as "spectators" we were invited to participate in the selection of the prize-winning contestants.

Undoubtedly many of us have ourselves experienced the sensation of competing for a prize; possibly a fellowship in some university granted as the reward for high scholastic attainment, or maybe only a cash award for submitting a particularly effective advertising slogan.

No argument is here advanced against this practice of pitting one's ability against that of others to earn a prize as the reward of accomplishment, for the motive is perfectly justifiable and the winners well deserve all the attention they attract. Mention is made of it simply to present by comparison a clearer conception of another type of extraordinary human endeavor in which the motive is less selfish and the accomplishment more useful.

In activity of this character, the goal as before lies in the accomplishment, but in the matter of the prize, if it be called such, there lies a vast difference—the producer shares his reward with mankind. This is what makes the efforts of the engineer and scientist the more creditable; particularly as the work often requires years of intensive study and arduous labor in the face of adverse conditions and bitter disappointments. Yet all too often the public accepts its share in the benefits as a birthright of its generation and gives little or no thought to the producer.

This lack of appreciative attention is largely the result of the scientist and engineer failing to claim it. If they would take time to address the layman and use language he can understand they could not only secure his interest but could hold it fascinated with stories of what they are doing. They nevertheless refrain from this practice because it is not characteristic of them to solicit attention. By nature they are industrious workers, and they recognize that to talk more would leave them less time to work.

However, there is another phase of the situation, an impersonal one. Only by a better public understanding and appreciation of their work can a full measure of their accomplishments be applied. For this purpose we doubt if they talk enough. As examples of how this can be done effectively, and without undue encroachment upon their working time, we point to the Franklin Institute in this country and to the Royal Institution in London where for the last century lectures have been delivered annually by distinguished physicists and chemists—Davy, Faraday, Lord Kelvin, and Sir William Bragg, to name but a few. How intimate a contact these lectures establish with the public is indicated by the fact that the programs include talks especially prepared for children.

An expansion of this type of publicity would be both popular and useful. We would thus become more familiar with these workers and would acquire a first-hand knowledge of what they are doing for us. But even under the present circumstances none of us should be without knowledge of those to whom we are most indebted. Their identification is periodically furnished by the granting of such internationally distinguished awards as the John Fritz Medal, the Franklin Medal, the Rumford Medal and the Kelvin Medal. It gives us great pleasure to present on the opposite page a recent photograph of Elihu Thomson, the latest recipient among those who strive for the benefit of mankind, not for medals, but to whom a medal is eventually awarded for great accomplishment in just that type of service.

New Fields of Research for Power Development

By E. W. Rice, Jr.

Honorary Chairman, Board of Directors, General Electric Company

We are pleased to have been extended permission by the London Power Conference to print the following exhaustive abstract of this paper which was delivered at that historic gathering last July. The fact that it was selected for presentation at the conference is in itself a hallmark of international merit, but this does not indicate that it is a fascinating story as well. It is an exceptionally interesting and readily understandable word survey of what our past and present research has accomplished and what trends of investigation appear to be most worthwhile in the future.—Editor.

HISTORICAL REVIEW

Some fifty years ago, Ulysses S. Grant, President of the United States, touched a telegraph key in Washington. A current of electricity flashed to Philadelphia, opening the steam throttle valve of the giant Corliss engine in Machinery Hall. This was the beginning of the world's first great International Exposition, the Centennial Exposition of 1876. I remember the awe inspired by this mammoth engine, the giant power of that time.

Looking backward, it is difficult to realize that this great machine developed only 1000 h.p. There are in daily operation in the United States alone some hundreds of power units in the shape of steam turbines each one equal in power to twenty such engines, while the giant power turbine of today will do the work of one hundred of that Corliss engine in 1876.

At the same Centennial Exposition were shown the original "speaking machine" or telephone of Alexander Graham Bell, and two exhibits of dynamo-electric machines, one by Gramme of France, the other by Wallace of America. The machines of each exhibitor were shown operating single arc lamps. They were also used to demonstrate that a dynamo-electric machine was reversible, and when supplied with electricity would act as a motor and give out mechanical power. The current generated by one machine was conducted through about 20 ft. of wire to another which, operating as an electric motor, drove a small centrifugal pump.

These little exhibits, the telephone and the dynamo, were scarcely noticed by the multitudes which crowded about the big Corliss engine, and probably no one had any conception that these "novelties" would, in the span of a short lifetime, revolutionize the world and usher in a new era of electric power.

This illustrates a point which I wish to make: that is, the difficulty of selecting with any certainty the relative importance of researches which should be made in the field of electric power or in other human activity. I admit the weakness of my "selectivity" sense, but am unable to resist the temptation to speculate in such a fascinating field.

* * * *

To furnish a background for his speculations as to the future, Mr. Rice continued his review of past developments in the generation and utilization of electric power. Beginning with the discoveries and inventions that made possible the building of electric generators of sufficient capacity and economy to utilize the then existing steam power, he briefly recorded the early commercial applications of electricity to lighting, the propulsion of street cars, etc. He then reviewed the introduction of the multi-phase alternating-current system and described the far-reaching results which this has had upon the supplying of power for industrial and domestic purposes. The later demands for much larger generating units and transformers, and for higher transmission voltages, were next given consideration together with the growth in railway, industrial, and marine motor applications, also electric heating, electrolytic processes, and the development of incandescent lamps, meters, and radio. The story of the research work done to produce better incandescent lamps he stated to be as fascinating as a tale of the Arabian Nights.

* * * *

DEVELOPMENT OF ELECTRIC POWER BASED UPON RESEARCH

While passing in review the progress made in supplying electric power for our benefit, of which I have given but the briefest sketch, and to which each one is able to add indefinitely, one may ask, "What has this to do with Research?" The answer, I believe, is that research is the foundation upon which this marvelous accomplishment has been built—the research of hundreds of able scientists and engineers in all civilized countries. We think at once of Davy, Faraday, Henry, Ampere, Weber, Helmholtz, Edison, Swan, Elihu Thomson, Steinmetz, to mention but a few.

No better example of scientific research, systematically and fruitfully followed, can be found than in the work of Faraday, whose accounts in his "Experimental Researches" will remain a model and a stimulus to scientific endeavor for all time.

The researches of Hadfield showed us that relatively large quantities of silicon added to sheet steel would reduce the hysteresis and eddy losses. It is true that difficult and costly experimental work, followed by skillful and refined manufacturing methods, were needed to make this new material available in the quantities and at the costs needed. But all this was forthcoming only after the important fact of the existence of such material was made known.

So, also, while the early waterwheel developed an efficiency of but 75 to 80 per cent, as the electrical art progressed larger and more efficient wheels were required, and serious research was required to determine the relations needed to avoid losses, with the result that the modern waterwheel has attained an efficiency of 91 per cent. As the electric generator driven by these waterwheels has also progressed to an efficiency of 98 per cent and over, the combined efficiency is somewhat in excess of 90 per cent. While the waste is small, the importance of conserving our water demands that even this high efficiency be improved, and the obvious point of attack is the waterwheel.

The Diesel engine is a remarkable instance of scientific research in the mechanical field. In large units 0.4 lb. of oil per b.h.p. is required, using 18,500 B.t.u. oil. This corresponds to the high thermal efficiency of about 31 per cent (11,000 B.t.u. per kw-hour, including auxiliaries). Unfortunately, however, its use as a prime mover for electric power is relatively restricted, because it has the serious limitations of all reciprocating apparatus as compared with rotating apparatus—limitations in speed, which result in limitations in the relative size of units compared with the steam turbine or waterwheel. As the electric generator has no such limits, it is important that the prime mover should be equally free.

The early steam generator unit had a "thermal efficiency" of about 14 per cent. We are using the term "thermal efficiency of the steam turbine electric unit" as the ratio of the B.t.u.'s. in the kilowatt-hours delivered by the generator to the busbars, divided by the B.t.u.'s. in the steam supplied to the turbine, less the B.t.u.'s. returned to the boilers in the condensate. By a long series of difficult researches as to the flow of steam in nozzles and buckets, by increasing the steam pressure, improvement in vacuum, and general increase in size of units, the thermal efficiency of the steam turbine electric unit has been greatly improved.

In machines of 30,000 to 50,000 kw., with steam pressures of 230 to 250 lb., steam temperature 625 to 650 deg. F., vacuum 29 in., without reheating between stages, a thermal efficiency of about 27 per cent has been obtained. Table I sets forth the progress made in the efficiency of such units in the United States from 1903 to 1923.

In units now under construction of 30,000 to 50,000 kw., with steam pressure of 375 lb., temperature 700 deg. F., vacuum 29 in., without reheating between stages, but with steam extraction for feed heating, an efficiency of about 30.5 per cent is expected.

In units now under construction of 50,000 to 60,000 kw., steam pressure 550 lb., temperature 725 deg. F., vacuum 29 in., with single reheating between stages, an efficiency of about 33.1 per cent is expected.

TABLE I

Year	Apparatus	Gauge Pressure per Sq. In.	Steam Temp. at Throttle Deg. F.	B.t.u. per Kw-hr.	Thermal Efficiency of Turbine Unit in Per Cent
1903	5000-kw. vertical turbines..................................	175	378	23500	14.5
1914	20,000-kw. horizontal turbines............................	200	588	14500	23.6
1923	30,000 to 35,000-kw. horizontal turbines, average good practice...	230	625	13350	25.6
1923	Most efficient stations 30,000 to 45,000-kw. turbines........	230–250	625–650	12500	27.2

A study has also been made of units of 100,000 kw., operating at 1200 lb. steam pressure, temperature 725 deg. F., vacuum 29 in., reheating twice between stages, which indicates a possible efficiency of about 38 per cent.

The results expected from these steam turbine electric units are set forth in Table II.

During the period of development of the turbine electric unit, great improvement has taken place in the steam boiler due to increased size, improved methods of firing, superheating, increased temperature of the feed water, etc. These improvements in both the steam boiler and the turbine electric units have co-operated to advance the "thermal efficiency" of the combined "plant efficiency" from about 10 per cent in 1903 to about 19 per cent in the modern station using 30,000 to 45,000-kw. turbines without reheating.

TABLE II

Year	Apparatus	Gauge Pressure per Sq. In.	Steam Temp. at Throttle Deg. F.	B.t.u. per Kw-hr.	Thermal Efficiency of Turbine Unit in Per Cent
1924	New stations, 30,000 to 50,000-kw. turbines, steam extraction for feed water, but without reheating between stages.......	375	700	11200	30.5
1924	New stations being erected, 35,000 to 60,000 kw., steam extraction and single reheating between turbine stages.......	550	725	10300	33.1
	Proposed new stations, 100,000 kw., single reheating between stages..	550	725	10100	33.8
	Proposed new stations, 100,000 kw., two reheatings between stages..	1200	725	9000	38.0

TABLE III

Year	Apparatus	Gauge Pressure per Sq. In.	Steam Temp. at Throttle Deg. F.	B.t.u. per Kw-hr.	Equivalent Lb. of Coal per Kw-hr.	Thermal Efficiency of Plant in Per Cent
1903	5000-kw. vertical turbines........................	175	378	37000	2.64	9.2
1914	20,000-kw. horizontal turbines....................	200	588	22000	1.57	15.5
1923	30,000 to 35,000-kw. horizontal turbines, average good practice................................	230	625	20000	1.43	17.1
1923	Most efficient stations 30,000 to 45,000-kw. turbines	230–250	625–650	18000	12.8	19.0

This improvement in efficiency of steam turbine electric plants is disclosed in Table III.

"Plant efficiency" takes account of all losses in boilers, flue, and station operation. It is equal to the B.t.u. equivalent of a kilowatt-hour (3414 B.t.u.) divided by the B.t.u.'s. in coal consumed per kilowatt-hour.

Coal is assumed to contain 14,000 B.t.u. per pound, which coal is available to the large companies on the eastern seaboard of the United States.

In stations now being erected with units of 30,000 to 50,000 kw., increased steam pressure and steam extraction for feed water, but without reheating between stages, a thermal efficiency of slightly under 22 per cent is expected. Other stations now being erected with units of 35,000 to 60,000 kw., 550 lb. pressure, with steam extraction and single reheating between stages, and operating on "base loads," that is, about 100 per cent load factor or capacity factor, a "plant thermal efficiency" of slightly under 24 per cent is expected.

In stations with units of 100,000 kw., 550 lb. pressure, with single reheating between stages, a plant efficiency of 24.1 per cent is expected. It is also estimated that if the pressure were raised to 1200 lb. and reheating twice between stages were adopted, a plant efficiency of about 26 per cent would be possible.

The results expected from the latest stations, using the largest steam turbine electric units which are either under construction or being considered as possibilities of the near future, are shown in Table IV.

Twenty-seven of the largest steam electric stations in the United States sold, in 1923, 18,500,000,000 net kilowatt-hours. If this output had been generated entirely by the stations equipped with the latest commercial apparatus shown in Table IV, the annual saving in coal consumption in the twenty-seven plants would have been about five million tons.

The foregoing twenty-seven stations produced about 40 per cent of the total kilowatt-hours output sold by steam central stations in the United States in 1923. As the smaller stations were less economical, it is fair to assume that if the 1923 output had been supplied by the most economical units in the large stations, a possible saving of not less than 12,500,000 tons of coal would have been realized.

TABLE IV

Year	Apparatus	Gauge Pressure per Sq. In.	Steam Temp. at Throttle Deg. F.	B.t.u. per Kw-hr.	Equivalent Lb. of Coal per Kw-hr.	Thermal Efficiency of Plant in Per Cent
1924	New stations, 30,000 to 50,000-kw. turbines, steam extraction for feed water, but without reheating between stages	375	700	15800	1.13	21.7
1924	New stations being erected, 35,000 to 60,000 kw., steam extraction and single reheating between turbine stages	550	725	14500	1.04	23.6
	Proposed new stations, 100,000 kw., single reheating between stages	550	725	14200	1.01	24.1
	Proposed new stations, 100,000 kw., two reheatings between stages	1200	725	12800	0.91	26.6

Turbine wheels and buckets were found at times to be subject to accidental breakage although designed with large factors of safety under normal conditions of operation. It was finally discovered that the trouble was due to vibration of a special but definite nature. It was only after much research that the factors causing this dangerous vibration were discovered, and a definite remedy applied.*

Numberless researches were required to bring the modern dynamo to its present state of perfection, such as to determine the laws of hysteresis, of eddy currents, the thermal gradient of different insulations, the dielectric strength of various natural and artificial insulations, the effect of temperature on dielectric strength of various materials, the life of materials at different temperatures, the laws of permeability, of conductance or resistance, etc.

Similar researches were needed to determine the rupturing distances of air, oil, and other materials, when subjected to electrical pressure; the influence upon the magnetic properties of steel, of alloying it with tungsten, nickel, etc.

Special research was invaluable in bringing heating devices to their present state of usefulness. For example, in heating devices, a wire made of alloy iron, nickel, and chromium, capable of operating at a red heat without oxidation, was developed as a result of considerable scientific research.

I have already pointed out how incandescent lamps of every type—carbon, tantalum, and tungsten, vacuum and gas-filled—have been the subject of numerous exhaustive researches, many of the most profound and scientific nature.

FUTURE FIELD FOR RESEARCH

As the dynamo has been brought to the remarkable efficiency of 98 per cent in the large sizes, there would appear to be little call for further research. However, efficiency of conversion is only one factor in utility. There remains the possibility of the better use of materials or the discovery of better materials to reduce weight and cost. This applies to all materials used in the dynamo: steel, copper, insulation, etc. I will reserve discussion of possible fields of research of this character until later in this article, as these materials are used in all the different fields under discussion.

The greatest source of primary power is found in coal and oil—stored sunshine. With all our advances, the steam turbine only converts, even in the largest and most efficient units now in operation, about 30 per cent of the available energy in steam into mechanical power for driving the electric generator. This may be increased to 35 per cent, possibly 40, with improvements under way in the steam-boiler-turbine cycle

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* The solution of this problem was largely due to Wilfred Campbell, whose recent death was a great loss to engineering.

Further research and experiments are needed to improve this ratio, and are actively sought.

A most promising field is being explored by W. L. R. Emmet in the use of the vapor of two fluids, mercury and water, by which a thermal efficiency of over 44 per cent of the power units has been obtained, equal to 34 per cent thermal plant efficiency. The Emmet process has the great advantage of conserving the existing investment in steam turbines, only replacing the present steam boilers and adding the mercury boiler and its turbine which feeds its added energy directly into the existing electrical network.

There are certain obvious limitations or objections to the use of mercury, which Mr. Emmet has met in a thoroughly practical and efficient manner. However, it is unlikely that mercury is the only available material, and researches are under way for the discovery of other such fluids. Such research work should be continued and will, we believe, be richly rewarded.

The method of extracting the heat energy of fuel through the medium of several fluids operating in a series of stages is, perhaps, the practical answer to the long sought gas turbine.

Sunlight, including all radiations from the sun, is the source of our commercial power, no matter what the intermediate agent—coal, oil, water, or wind. The direct transformation of solar radiation has been sought, but thus far without success. It is probably too intermittent to be utilized directly because of the cycle of night and day and the intervention of clouds. The most promising solution would seem to come through storage in growing vegetation. Improved methods of selection and of the acceleration of such vegeto-chemical storage of the sun's radiation may be discovered and should be diligently sought.

It has been suggested that the photo-electric process may contain the germ. Such phenomena should be investigated, if for no other reason than that we are here dealing with the electron.

All methods which contemplate the direct conversion of solar radiation into mechanical or electrical energy are largely dependent for their value upon storage of electricity, and this suggests that our only method of storage, the storage battery, has advanced but little with the passing years. A radical improvement is certainly needed. We must admit that no promising opening or "lead" has yet been disclosed, but we must not be discouraged. The problem is one for the chemist, and he is a worker of miracles.

The source of power which we must except from solar radiation is the power obtained from volcanic regions through holes bored into the earth, as has already been successfully developed in Italy.

Another possibility exists in the interesting and important suggestion made by Sir Charles Parsons in 1904, and again in 1919, of boring a great hole 10 to 12 miles deep in some convenient and suitable place, to utilize the internal heat of the earth. This suggestion should not be allowed to lie fallow. I heartily agree with Sir Charles in his statement that the cost of such an experiment is trivial compared with the value of the possible information which might be gained by the investigation into this unexplored region of the earth. The cost would be much less than that of a single battleship. If only the people and their representatives had the faith and vision of Science, the value of such an idea would have been put to practical test long ago. It is a big idea, worthy of a nation's enthusiastic support; in fact, it is worth undertaking as an international scientific enterprise—a suitable subject for co-operative work between friendly nations.

Research of the elements of overhead transmission should be continued along the lines which have yielded such a harvest—a study of the limits of electric pressure, of corona losses, insulators, size and type of conductors, etc.

During the past 20 years the transmission voltage in use for overhead lines has grown from 60,000 to 220,000 volts, which two large systems in California are now using. About 75,000 to 100,000 kw. per circuit is transmitted over a distance of 250 miles with highly satisfactory results. Higher voltages appear technically feasible. Apparatus has already been constructed for test purposes at much higher voltage, and laboratory experiments have been conducted at over a million volts. If it is necessary to transmit electricity over longer distances, the limitations would appear to be largely economical rather than technical—the balance between interest, maintenance, cost of operation, and the cost of the power lost; that is, Kelvin's law. It has been found in America that such 220-kv. lines, capable of transmitting 100,000 kw. at a line loss averaging 15 per cent, cost from $20,000 to $25,000 per circuit mile. At 250 miles, this is equal to $5,000,000 to $6,250,000. This makes the cost per kilowatt for line alone between $50 and $62.50.

It is unlikely that a higher pressure than 220 kv. will be required for general power transmission for some time, as this pressure is apparently satisfactory in cost, efficiency, reliability, freedom from serious corona loss, and general stability when operating at 50 to 60 cycles.

There are a few large undeveloped water powers in the world with a million kilowatts or over of potential power, unfortunately located some 500 to 1000 miles from their natural market. These exceptional cases will require special treatment, perhaps 350,000 volts, with a reduction of frequency to 25, or even 10 cycles. However, the use of direct current for such special cases is well worth consideration, and for this purpose the vacuum tube challenges attention, as it is capable not only of rectifying alternating current but also of converting direct current back into alternating current.

The vacuum tube is no longer the feeble device of a few years ago, when it was capable of handling only a few watts. Tubes are now regularly manufactured capable of handling 20 kw. or more. Tubes of larger capacity are in process of development. No limit has yet appeared, so that we may, without straining our imagination, look to the idea of high-power vacuum tubes, capable of handling, when operated in multiple, the power required in such applications.

Underground cables of 60,000 volts alternating current are in operation and cables for higher voltages are under test. A great need exists for underground cables of 100,000 volts or higher. Some have been made experimentally. More research and experimental work in this immediate line is required, as apparently present design and manufacturing methods are not sufficiently advanced to produce 100,000-volt cable in commercial quantities at practical prices.

Additional research of an electrical nature does not seem to be demanded in order to accelerate the electrification of steam railroads. All the necessary electrical and mechanical machinery has been produced and tested by years of practical experience. The advantages of electrification are well known and have been thoroughly advocated; such as fuel economy, cleanliness, reliability, low maintenance, increased ability to handle traffic at all times, over all profiles. Progress in railroad electrification has been made all over the world, but painfully slow to the impatient electrical engineer—slow compared with other electrical developments. It has been claimed that the railway companies were confused because of the multiplicity of methods offered by competing engineers and manufacturers, with especial reference to the claims of the so-called high-tension direct-current and the single-phase alternating-current systems. That this has seriously delayed action is doubtful, as the railway officials have available reliable data and ample experience upon which to exercise discriminating judgment in this, as in other affairs. The cause must be sought elsewhere, and is probably to be found largely in the great initial cost of general electrification.

It is well known that for many years railroads in general have had to face a most difficult financial situation, involving high operating costs and low revenues. They have naturally confined capital expenditures to those absolutely necessary for existence.

The general introduction of the so-called superpower or giant power stations and their interconnection so as to form a great power network from which electric power may be drawn at any time, in any quantity, and for any purpose, may hasten the time when the railroads will electrify, as it will enable them to purchase reliable electric power and avoid a substantial portion of the large initial capital outlay which would otherwise be required.

A rather unexpected application of electric power has recently been developed in the use of high-frequency currents to operate special forms of electric furnaces, and for special heating purposes. For example, the metal parts of vacuum tubes or the contents of insulated crucibles may be heated to any desired temperature by being placed within the influence of a few turns of wire or of a coil of water-cooled pipe, the action taking place through glass or other insulating materials, and at a considerable distance. This is a most valuable tool for research work in many fields.

Important developments have taken place in the X-ray tube, that most interesting piece of apparatus, and in its application to medicine for diagnostic and therapeutic purposes and also in its use in the arts. Tubes which operate at 250,000 volts are regularly manufactured, and tubes for 500,000 volts are under way.

Research work by this most important of research tools is continuous, but should be accelerated. The X-ray spectroscope is a tool by which physicists are able to study the nature of atomic combinations, and, as it were, look into the interior of matter and see the actual position and arrangement of atoms in a crystal; in short, it does for us in the infinitely small what the light spectroscope has done in disclosing the nature of celestial bodies in the depths of infinite space.

The discovery of the electron and its identification with the ultimate particle of negative electricity, the discovery of the positive nucleus, the theories of Rutherford and Bohr as to the structure of the atom, and the recent discoveries of the definite measurable arrangement of atoms in the crystals of many substances, have given us an entirely new grasp of the atomic structure and the nature of matter. Our imagination has been stimulated and our courage increased to the point where we may now look forward with some confidence to the solution of such mysterious qualities of matter as electrical conductivity and the phenomena of magnetism. The electric conductivity of copper and the magnetic permeability of iron have been regarded as fixed and unchangeable qualities. Electric power is dependent upon the fortunate fact that we have two metals in abundance possessing these two peculiar and valuable properties—copper and iron. We have found no substitutes; no way of increasing the conductivity of copper or magnetic permeability of iron. With our new knowledge we may fairly raise the question: "How can the conductivity of copper be increased and the permeability of iron be raised?"

With our new tool, the X-ray, supplemented by the radiations of radium in the hands of such experimenters as J. J. Thomson, Rutherford, Aston, the Braggs, and many others, we are led to believe that we may eventually understand the exact arrangements of the atoms which confer these important qualities, and with such knowledge, that we may then learn how to make similar combinations with other metals, and eventually produce better materials.

The wonderful experiments of Kamerleigh Onnes, who found that a number of metals have practically no resistance at very low temperatures, demonstrate that we have much to learn on this subject.

There are great limitations to our present knowledge waiting to be removed. For example, why does the addition of such an insignificant quantity as 0.1 per cent of silicon to copper reduce its electrical conductivity to 65 per cent; or even a microscopic quantity of phosphorus, 0.002 per cent, reduce the conductivity of copper to 94 per cent.

Researches in magnetism have been under way for years, but no radical improvement has resulted since the discovery of silicon steel. After many years we had succeeded in regularly producing silicon steel with a loss of less than 0.6 watt per pound at 60 cycles and 10,000 lines density per square inch, and by laboratory methods have attained 0.48 watt.

And now suddenly appears a new alloy—50 per cent iron and 50 per cent nickel—having a watt loss of but 0.4 per pound.

Another alloy of 80 per cent nickel and 20 per cent iron, called perm-alloy, has an extraordinary permeability at low density.

It is believed that the causes of these extraordinary phenomena must be found in the atomic arrangements. It has been known for years that magnetized iron loses its magnetism at red heat. X-ray analysis now discloses that magnetic iron has a certain definite arrangement of atoms and that the iron atoms lose this arrangement, as well as magnetism, when the iron is raised to red heat.

We now find that the introduction of another element into the iron distorts the atomic arrangement in a definite, measurable amount. Such facts encourage us to hope that careful research and experiment will in time determine "why the addition of nickel to iron increases its permeability at low density, and the addition of cobalt to iron increases the permeability at high density," and point the way to new combinations of great value.

It is believed that tensile strength, hardness, resistance to corrosion, etc., depend partially at least on the arrangement of the atoms in the crystal. "Monel metal, a natural alloy of nickel and copper, has a high resistance to corrosion, but a low elastic limit. The addition of about 3 per cent aluminum more than doubles the elastic limit without affecting corrosion." The reason for this is unknown. The X-ray spectrum should throw light upon the subject and perhaps "make possible sometime with paper and pencil to work out new alloys of almost any desired characteristics, designing the space lattice structure of the atoms much as a civil engineer designs a truss structure of a bridge."

The phenomena of electrical conductivity in vacua are fairly well understood, due to the work of J. J. Thomson, Langmuir, and others, but we do not yet know whether there is an upper limit to the potential gradient which may be used in high vacua. Such information will be of importance in the design of future superpower tubes.

The highly complex phenomena of gaseous or vapor conduction are not so well understood. Researches in this field which are going on, and the study of ionization phenomena, may lead us in time to more efficient methods of producing light. Our present efficiencies are, as is well known, very small—from 4 to 8 per cent in our best lamps.

The mercury rectifier is a device which, as compared with the vacuum power tube, is especially adapted for handling heavy currents and operating at high efficiency at moderate voltage ranges. This device will undoubtedly be eventually improved and made more reliable by a better understanding of this same phenomenon of ionization.

Insulation is as important a property of certain kinds of matter as electrical conductivity or magnetism. Without it we could not build electrical machinery or transmit and guide the electricity if made. We know a good deal about the properties of insulating materials and something of the nature of their failure, but the exact atomic structure is unknown. It would seem that no more important field of research could be suggested. If we could learn the fundamental nature of insulation, it is reasonable to expect that we would soon be in position to improve all of our electrical machinery, reducing its cost as well as the cost of our transmission lines. It might make underground cables of 100,000 or even 200,000 volts as practical as, and cheaper than, present overhead wire transmission.

The nature of lubrication is another interesting field for research. This property of lubrication is of exceeding importance in view of the necessity for designing the bearings of electrical machinery for highest possible duty. Its nature, as well as the exact mechanism through which oil loses its lubricating qualities, is unknown. We do not know why one oil is a good lubricant for some metals, and poor for others, while another oil may show just the opposite results. Researches are in progress in these lines and should be extended.

CONCLUSION

If I appear to have unduly stressed the contributions of America to the development of electric power, my excuse is that I am naturally more familiar with such contributions; but I wish to make clear that we are all alive to the debt which the art owes to the workers in all civilized countries. Electric power is the product of international effort, and a monument to the benefit of international co-operation.

It is an excellent example of that pooling of interests and division of labor which intelligent men all over the world look forward to as the ultimate goal of civilization. Scientists have been restricted by no national boundary; results have been published broadcast for the benefit of all mankind. "Engineering is based on scientific discovery, and therefore the recognition and support of scientific research in all fields, in all countries, is of paramount importance. Any new discovery, such as a new method of power production, transformation, or utilization, disclosed anywhere in the world will soon be put to use in all the remainder of the civilized portions. We are therefore all equally interested in the advance of Science and Engineering, and ought to contribute our share in the necessary effort."

The opinion has been expressed that Science is progressing too rapidly for the average man to control wisely—that Science is making a Frankenstein monster that will destroy our civilization. I do not see the logic of such fear. It is true that every increase in man's control over Nature increases his power for evil as well as good, but man's nature is not changed, and I believe that the balance of power has been slowly passing to the good side. Education may not, but certainly ignorance cannot save us.

Everything depends upon the use we make of our new knowledge, and that depends upon our point of view. The spirit of Science is friendly, tolerant, and helpful. It is the spirit of service. The spirit of Science is not seen in the horrors of war, but in the victories of peace. Only the most friendly rivalry exists between the men of science in all countries. If the world can be inoculated with this scientific spirit, we need not fear the future.

The First Complete Electrification of an Open-pit Iron-ore Mine in Minnesota

By R. S. Walker

Consulting Engineer, The M. A. Hanna Company, Cleveland, Ohio

The service of electricity in iron-ore mining by the open-pit method is introduced by a concise historical review of the discovery of ore in northern Michigan and Minnesota, and of the gradual development of this great mine area. In this article the author points out that the geology of the Central Mesabi ore deposit makes open-pit mining very economical, since the ore bodies lie comparatively close to the surface. That this method possesses numerous advantages is apparent from the production figures given in the article. The early equipment was naturally of small capacity and did not permit of large scale production. Modern electric equipment was first introduced in open-pit mining on the Mesabi Range in 1920, when electric shovels were placed in operation. The success of this step led to the further adoption of electrically driven shovels and, this year, to the replacement of steam by electric locomotives at the Wabigon Mine. The specifications and operating costs of the electrical equipment at this mine are given in detail. The superior performance of this type of equipment and the savings it effects are an ample incentive to the widespread adoption of electrification in open-pit iron-ore mining.—Editor.

The "open-pit" mine, described in this article, is known as the Wabigon, and is located at Buhl, Minnesota, on the Mesabi Range. This range is the greatest producer of iron ore in the Lake Superior Region.

Before taking up the actual description of the electrification project, it may be of interest to give a brief outline of the Lake Superior Iron Ore Region, with particular reference to the Mesabi Range, and also a general résumé of the open-pit method of mining.

R. S. WALKER

LAKE SUPERIOR IRON ORE REGION

Location, Extent, and Development

The Lake Superior Iron Ore Region, as shown in Fig. 1, comprises the deposits in Michigan, Wisconsin, and Minnesota, and is divided into the Marquette, Menominee, and Gogebic Ranges in Michigan, the Baraboo, Mayville, and part of Gogebic Ranges in Wisconsin, and the Mesabi, Vermilion and Cuyuna Ranges in Minnesota.

The first iron ore in this region was discovered in 1844, near Teal Lake, at Negaunee, Michigan, by a party of Government surveyors on the now-called Marquette Range; and the first shipment, consisting of six barrels, was made in 1852, while regular shipments began in 1856. These shipments were made possible by the opening of the ship canal at Sault Ste. Marie in 1855.

The Menominee Range was discovered in 1873, and shipments began in 1887. In 1883 ore was found on the Gogebic Range, and shipments from there began in 1884.

In Minnesota ore was discovered on the Vermilion Range in 1884, and commercial shipments were made in the same year.

In 1890, the discovery of ore just north of what is now known as the Mountain Iron Mine constituted the first exploration of importance in bringing in the Mesabi Range. The Cuyuna Range was the last to be discovered. Low-grade magnetite ore was found there in 1904, and commercial shipments began in 1911.

The iron ore ranges lie at an average elevation of about 1500 ft. above sea level, and occupy a combined area of approximately 3800 sq. miles.

To gather some idea of the Lake Superior iron mining industry, it may be noted that during 1916 the total annual tonnage shipped from this region reached 66,672,359 tons, and at the end of 1923, or only 68 years from the date of the first commercial shipment, the grand total shipped had amounted to the tremendous figure of 1,133,133,035 tons. Of these amounts the Mesabi Range shipped 42,525,906 tons in 1916, or nearly 64 per cent of the total annual shipment; and it had a grand total of 643,349,633 tons to its credit at the end of 1923, or 56 per cent of the grand total of the Lake Superior district. When it is realized that the Mesabi Range was discovered only 32 years previous to 1923, one can appreciate the great output possible by open-pit mining.

As will be noted from Fig. 3, the Mesabi Range extends from a point about 55 miles north of Duluth, in a southwesterly direction for a distance of about 100 miles.

Geologic Formation of Central Mesabi Ore Deposit

A geologic vertical section of the Central Mesabi ore deposit is given in Fig. 2. The iron formation is a part of the Upper Huronian series, and is known as the Biwabik formation. This is comprised principally of ferruginous cherts termed taconite. The ore bodies occur in the Biwabik formation and generally are comparatively close to the surface.

The section shows in a general way the characteristic divisions of the iron formation and the relation of the ore bodies. The ore bodies have been formed in places where gentle folding of the formation has fractured it, and allowed access and free circulation of ground waters. The leeching and removal of silica gave rise to the alteration to the ore, and during the process caused a loss in volume which resulted in a settlement of the ore layers at the rock walls as shown in Fig. 2. The ores of the Mesabi Range are mostly soft hematites and limonites.

Methods Employed in Open-Pit Mining

Compared with other iron-ore districts, the Mesabi Range has great natural advantages, as the ore bodies occupy relatively shallow troughs having a large horizontal area and are covered with only a glacial drift. These conditions make possible the mining of a large proportion of the tonnage by what is known as the open-pit method. In this system the overburden is first removed by power shovels and then hauled to convenient "dumps," as illustrated in Fig. 4, which are located off the formation. This process is known as "stripping." The uncovered ore is then removed by power shovels direct into railroad cars for shipment. Open-pit mining has many advantages, such as permitting large daily output with large output per man, and great flexibility in that it allows quick increase or decrease in rate of output, and total suspension of operations without excessive charges for maintenance. A further advantage is that skilled operators are required only on the shovels and locomotives and all other work can be performed by common labor.

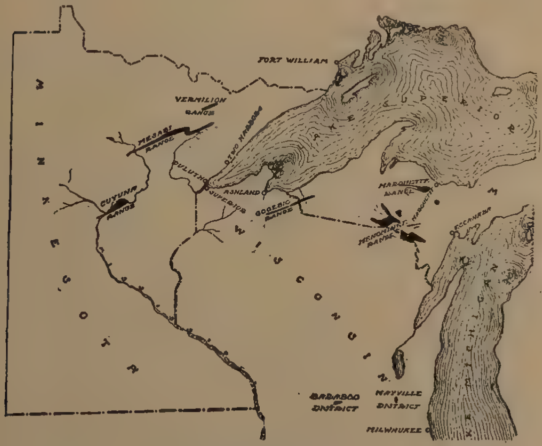

Fig. 1. Map Showing Location of Lake Superior Iron-ore Ranges

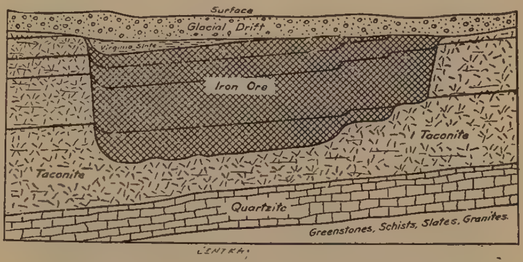

Fig. 2. Vertical Section Through Central Mesabi Ore Deposit, Showing Geologic Structure

The economical limit of stripping is generally considered to be one cubic yard of overburden to one ton of ore where the vertical depth of the overburden does not exceed two feet of stripping to one foot of ore. The character of the overburden must be considered, and in general approximately 150 ft. is taken as the maximum economical depth of overburden which can be removed.

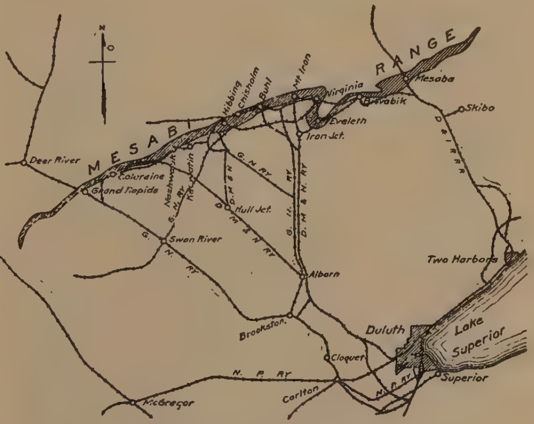

Fig. 3. Map Showing Location and Extent of Mesabi Range and Railroad Connections

The stripping is accomplished by removing "slices" or "cuts" over the area of the ore body. The depth of cut varies with the size and type of the shovel employed. With the

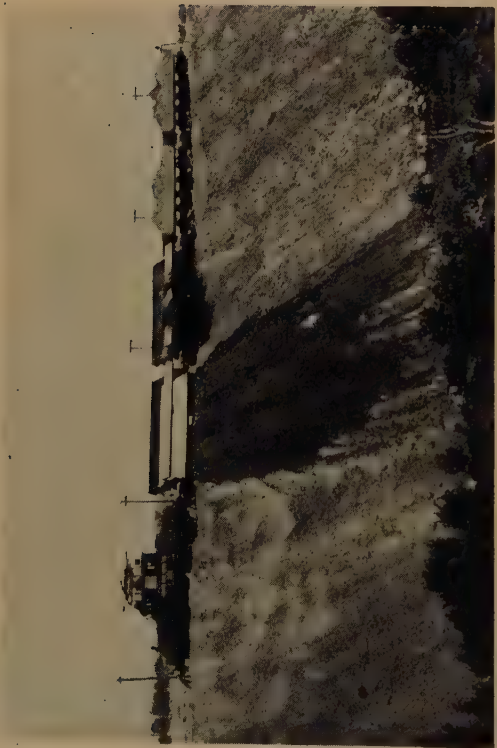

Fig. 4. Sixty-ton Electric Locomotive and 20-cu. yd. Dump Cars on Dump

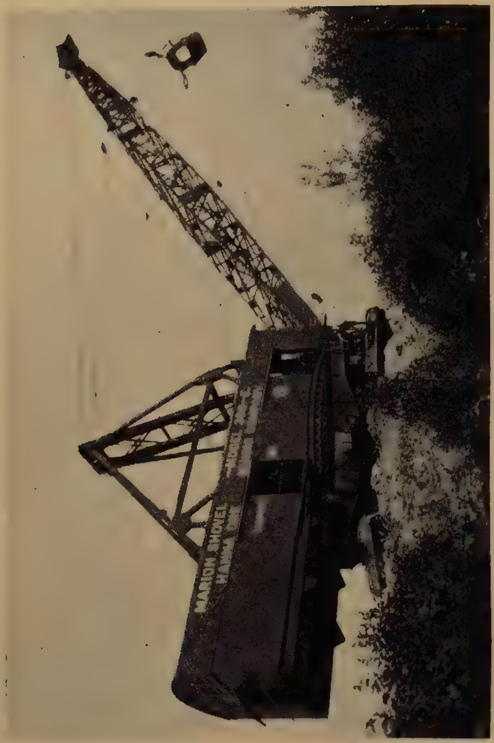

Fig. 5. Marion Shovel Fitted with 155-ft. Dragline Boom

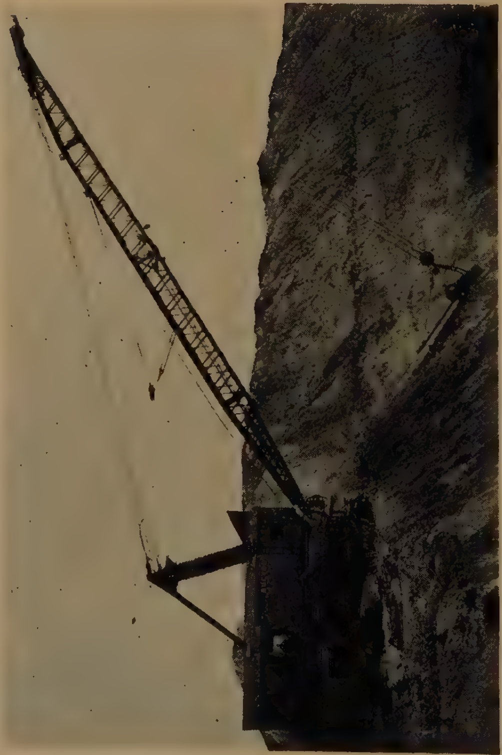

Fig. 6. Bucyrus Shovel in Operation Fitted with Dragline Attachment

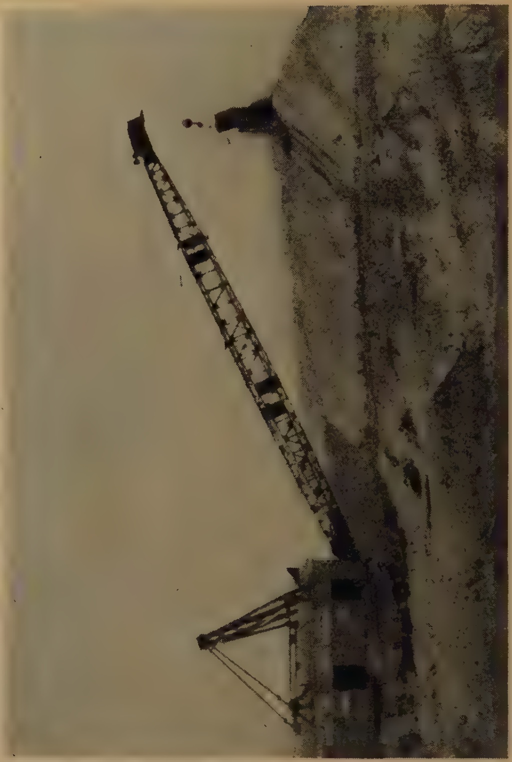

Fig. 7. Dumping Spoil in Dragline First Cut

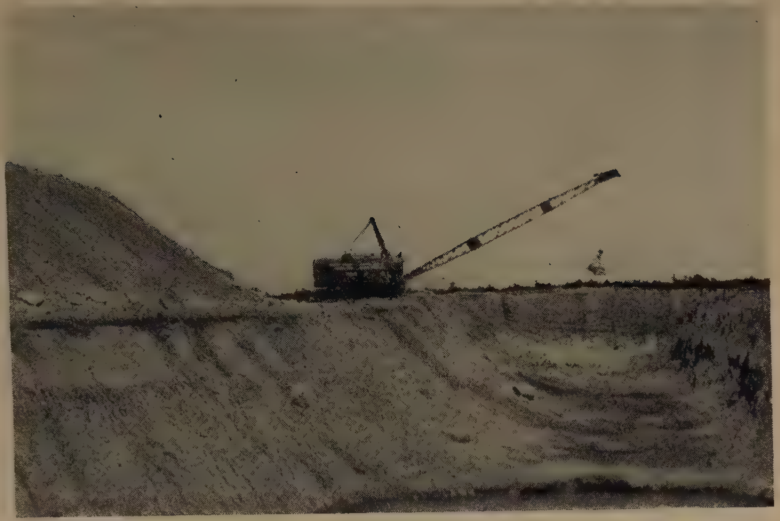

Fig. 8. Lowering Bucket for Digging Stroke in Dragline Second Cut

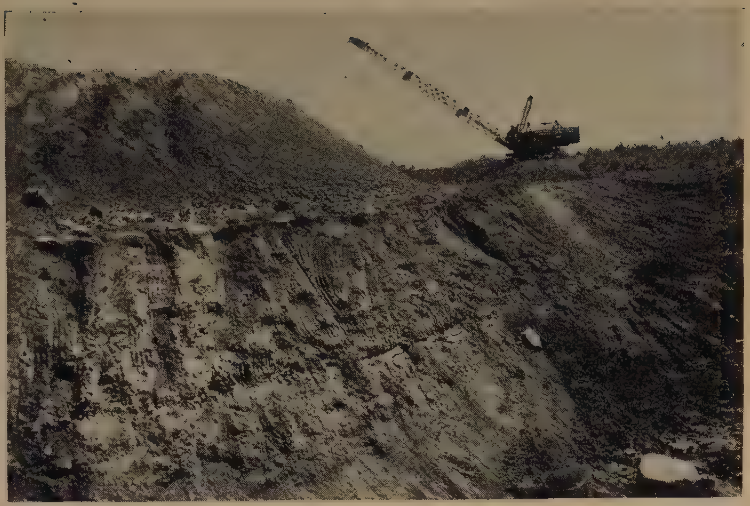

Fig. 9. Marion Shovel Stripping with Dragline Attachment

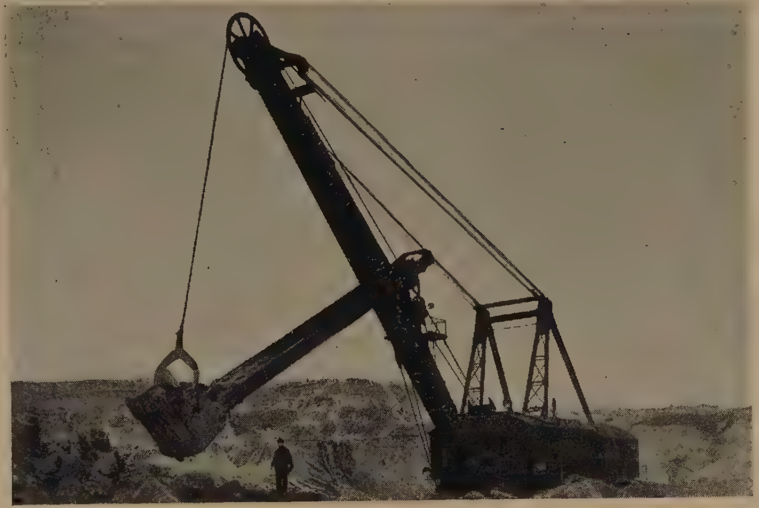

Fig. 10. Bucyrus Machine Fitted with Shovel

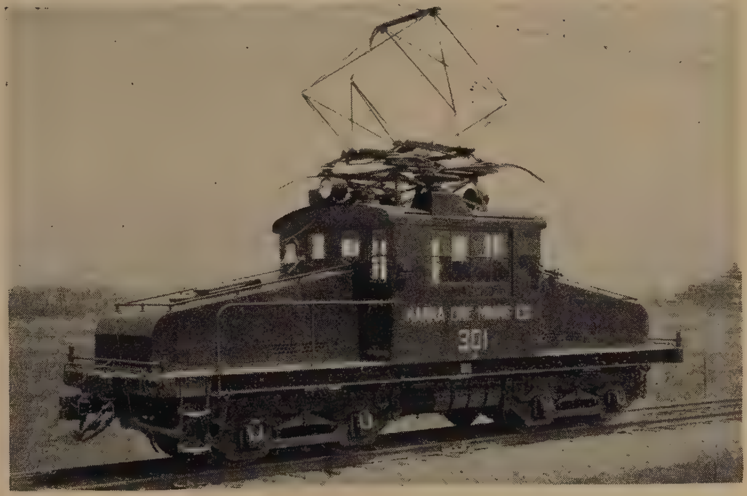

Fig. 11. Sixty-ton Electric Locomotive with Pantograph Raised for Service

railroad type of shovel, a 20- to 25-ft. cut is made, and the cars are spotted on a loading track at the same elevation as the shovel; but in the case of the 350-ton shovels a 30- to 36-ft. cut is made, and the cars are spotted on a loading track at the top of the cut above the shovel, as shown in the cover illustration of this issue. This procedure is repeated in a series of slices, the number depending on the depth of the overburden.

The track arrangement varies with the size and shape of the ore body, and the maximum economical grade. In the larger ore bodies it is possible to use a system of spiral tracks, but in the smaller and average pits a series of switchbacks is necessary. These switchbacks are confined to one side of the pit, and arranged so as to "tie up" the minimum tonnage of ore under them.

The "stripping dumps" where the spoil is wasted vary in distance from the mines, depending upon the district. In some cases it is necessary to haul the spoil some miles to a point which is entirely off the formation. In others, dumps can be made quite close to the pit. In recent years dragline attachments on the shovels, seen in Figs. 5, 6 and 7, have been used with success for stripping, in cases where dumping space immediately adjoins the ore. In these equipments 155-ft. booms and 5-cu. yd. Page-type buckets are used. The operation consists in taking a first cut of from 50 to 60 ft. deep, and dumping the spoil behind the machine, as illustrated in Fig. 7 (this procedure being known as overcasting). The machine is then moved behind the first pile and this spoil cast over again (recasting). Finally the machine is moved into the place occupied by the spoil from the first overcast, and a second cut taken, Fig. 8, dumping the spoil onto the spoil from the first cut. In this method of stripping no cars or locomotives are required and it is therefore more economical than the shovel method. Fig. 9 presents a comprehensive view of stripping as accomplished by this method.

It should be noted that the removal of ore, or "mining," follows the same procedure as the stripping, with the exception that the ore is loaded direct into railroad cars and hauled to the yards where the cars are made up into trains ready for the locomotives to haul to the ore docks.

Development of Equipment in Open-pit Mining

The development of open-pit equipment has been quite remarkable when it is considered that the first steam shovel of the railroad type, weighing about 35 tons and equipped with a one-half-cubic-yard dipper, was introduced on the Mesabi Range in 1893. At that time small wooden cars, varying in capacity from one to four cubic yards, were used with dinky-type locomotives weighing six tons. The tracks were 36-in. gauge, and laid with 20-lb. rails. The cars were dumped by hand, and the spoil spread in a similar manner. At the present time, railroad-type shovels weighing in excess of 100 tons, equipped with four-cubic-yard dippers, and a number of revolving-type shovels weighing in excess of 300 tons, and equipped with eight-cubic-yard dippers, are used. These shovels load into cars having capacities of 20 to 30 cu. yd. each, and are hauled by locomotives weighing from 60 to 100 tons. The tracks are all standard gauge, and laid with 80-lb. rails. The cars are automatically dumped by compressed air from the locomotive cab, and the spoil leveled by powerful spreaders propelled by locomotives.

After the introduction of the steam shovel in 1893, there was a period of 27 years in which no marked change was effected in stripping machinery on the Mesabi Range other than a gradual development towards larger and better equipment; and it was not until the year 1920 that a radical move was made, when the M. A. Hanna Company introduced the first electric shovels. These two machines, of the full-revolving type, shown in Figs. 5 and 6, weigh approximately 350 tons, and both were designed for use either as shovels or draglines. Fig. 5 and the illustration on the cover of this issue show the Marion machine equipped with both dragline and shovel booms. The electrical equipment on the two shovels is practically identical, and control is accomplished by the Ward-Leonard system comprising a five-unit motor-generator set and individual motors for each motion of the shovel or dragline. The Marion shovel is installed at the Wabigon Mine at Buhl, Minn., while the Bucyrus, pictured in Fig. 10, is located at the La Rue Mine at Nashwauk, Minn.

The second radical move was made in 1924, when electric locomotives were introduced at the Wabigon Mine. These locomotives, one of which is illustrated in Fig. 11, are of the switcher type and weigh approximately 60 tons. The power is supplied to the locomotives by an overhead trolley wire at 600 volts.

ELECTRICAL EQUIPMENT AT THE WABIGON MINE

The outline map of the Wabigon Mine, Fig. 12, shows the general procedure of stripping and mining as laid out for this property. The switchback arrangement of tracks in the pit, and tracks to dumps and yards are clearly shown. It will be noted from the cross-section that two slices of stripping and two of ore will be required. In this pit all the stripping and the loading of ore is handled by a 350-ton electric full-revolving shovel, which will work in a series of box cuts across the pit on each slice. The clean-up cuts and rock work are handled by a 60-ton full-revolving electric shovel mounted on caterpillar traction. The haulage power consists of three 60-ton electric locomotives.

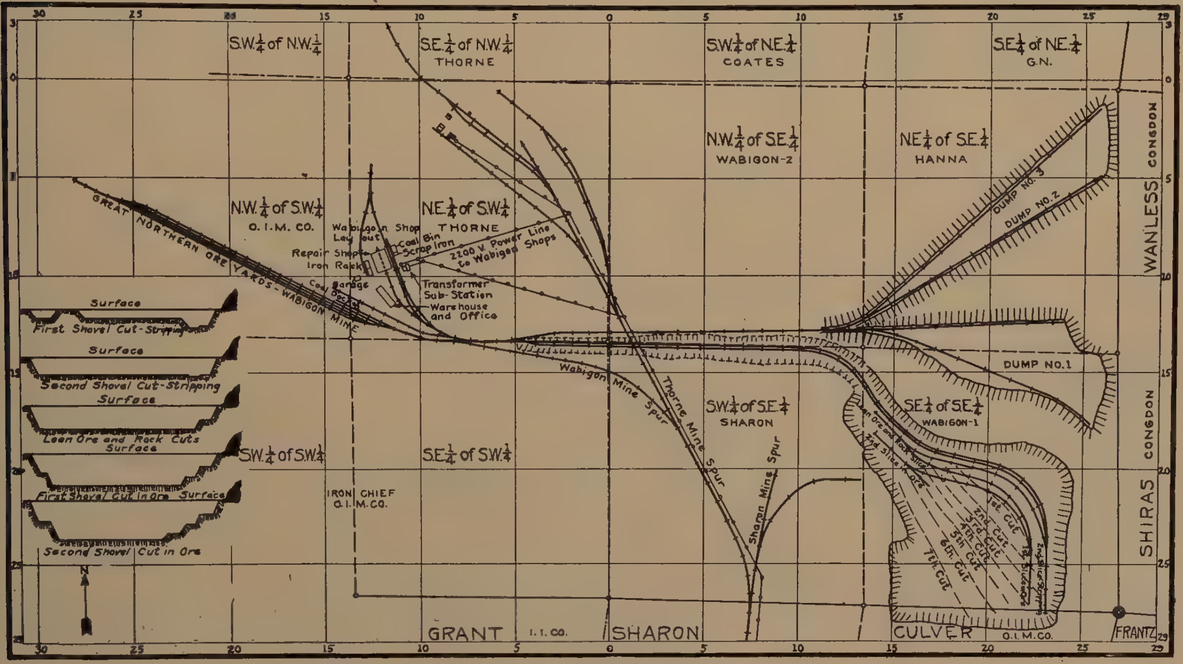

Fig. 12. Outline Map of Wabigon Mine

Power Supply and Distribution

Three-phase, 60-cycle, 20,000-volt power is purchased from the Minnesota Power and Light Company. A bank of three single-phase transformers steps down the incoming voltage to 2200 for the use of the shovels, and six transformers in two banks step down the incoming voltage to 445 for the synchronous converters which supply 600 volts, direct current, to the trolley haulage system.

The shovel supply is carried at 2200 volts on a pole line to the pit, and arranged to run as close to the shovels as practicable. The 350-ton shovel is provided with a cable reel attached to the machine, and the necessary cable for 2200-volt operation; whereas the 60-ton shovel is equipped with a reel wound with suitable cable, mounted on skids and dragged behind the shovel.

Trolley Wire System

After exhaustive investigation as to the relative merits of third-rail and overhead trolley wire systems, it was finally decided to use the latter. This decision was made from the standpoint of first cost, freedom of any obstruction in the case of derailments, more satisfactory operation when snow is on the ground, and general safety. On all main tracks the trolley wire is suspended over the center of the track by means of standard overhead material and at a height of 22 ft. above the rail. This allows sufficient clearance for moving a wrecking crane with boom down. So few derailments occur on the main tracks that it is not considered necessary to provide clearance for the crane with boom up.

On the loading tracks in front of the shovel a center trolley is not feasible, as it would interfere with the shovel dipper when loading cars, and also with the wrecking crane boom. It was therefore decided to use a trolley wire installed at the side at a distance of 10 ft. from the center line of the track and 15 ft. above the rail. This arrangement is diagrammed in Fig. 13. The wire is suspended from standards of a portable type ballasted with rock. The side trolley installation must necessarily be of a temporary nature, as the tracks are continually being shifted as the shovel cuts are finished.

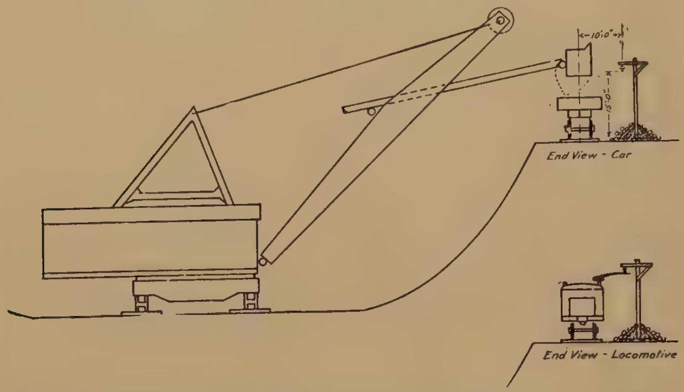

Fig. 13. Arrangement of Side Trolley Wire, Showing Clearance When Loading

On the dumps a construction is used similar to the shovel tracks, as again the tracks are moved from day to day as the dumps are filled. Each locomotive is provided with a pantograph collector mounted on the cab roof for main track work, and two special side-arm collector devices mounted on either side of the cab roof for use with the side trolley wire. One of these is shown in service in Fig. 14. All collector devices are air operated from suitable valves conveniently located in the cab. In this way the change from pantograph to side-arm collector or vice versa can be made while the locomotive is in motion. Care has been taken to provide suitable "leads" to both overhead and side trolley wires to prevent accident to the collector devices in case the operator should forget to move these at the correct time.

Substation

The direct-current substation, Fig. 15, contains two 300-kw., 1200-r.p.m., 600-volt synchronous converters, together with a six panel switchboard, and two converter starting panels. The switchboard consists of two panels for combined transformer and synchronous-converter equipments, two panels for automatic reclosing feeder equipments, and two panels for machine load-limiting resistor equipments.

By the use of load-limiting resistors it is possible to use 300-kw. capacity converters, and to run both machines for the full load required by three locomotives. Should it be necessary to take one machine out for repairs, it will be possible to operate the haulage at 75 per cent capacity. Furthermore, one machine has the economical capacity for handling the locomotive load when switching on Sundays and idle days.

By locating the substation adjacent to the mine machine shops and having the equipment semi-automatic, no attendant is required. The starting and stopping is taken care of by one of the machinists. Thermostatic protection is provided on the bearings of the converters, and automatic reclosing breakers on the feeders.

Electric Shovels

The electric shovels consist of one Marion, model 300 E, and one Bucyrus, model 50 B. Both machines are equipped with direct-current motors operated from motor-generator sets. In the case of the model 300 E, the control is full Ward-Leonard; and in the 50 B is partial rheostatic, the single generator having a drooping characteristic.

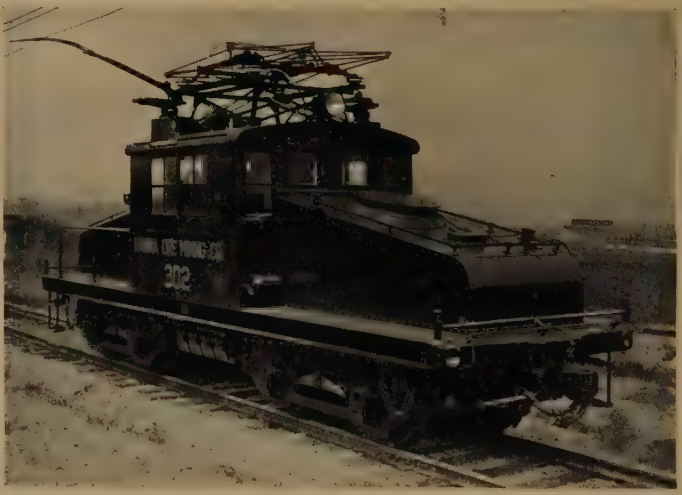

Fig. 14. Sixty-ton Electric Locomotive with One Side-arm Collector in Service and Pantograph Down

Principal Dimensions of Marion 300 E

Length of shovel boom, 80 ft.
Length of dipper handle, 52 ft.
Capacity of dipper, 8 cu. yd.
Maximum height of dump above rail (boom at 45 deg.), 56 ft.
Dumping radius at maximum dumping height, 95 ft.
Radius of cut at 40-ft. elevation, 99 ft.
Radius of cut at bottom of pit, 60 ft.
Length of dragline boom, 155 ft.
Approximate working weight, 690,000 lb.

Electrical Equipment for Marion Machine

- Motor-Generator Set
  - Synchronous motor, 435 kv-a., 60 cycle, 2200 volts, 3 phase, 1200 r.p.m.
  - Hoist generator, 250 kw.
  - Swing generator, 50 kw.
  - Crowd generator, 50 kw.
  - Exciter, 20 kw.
- Motors
  - Hoist, two, 175 h.p.
  - Swing, one, 75 h.p.
  - Crowd, one, 75 h.p.
- Control
  - Ward-Leonard System

Principal Dimensions of Bucyrus 50 B

Length of shovel boom, 36 ft.
Length of dipper handle, 19 ft.
Capacity of dipper, 1½ cu. yd.
Maximum dumping height above rail (boom at 55 deg.), 34 ft. 9 in.
Dumping radius at maximum dumping height, 31 ft. 3 in.
Radius of cut at 8-ft. elevation, 33 ft. 7 in.
Approximate working weight, 125,500 lb.
Caterpillar traction.

Electrical Equipment for Bucyrus Shovel

- Motor-Generator Set
  - Induction motor, 100 h.p., 60 cycle, 2200 volts, 3 phase, 1200 r.p.m.
  - Generator, 65 kw., 300 volts, direct current, differential field winding.
- Motors
  - Hoist, 75 h.p.
  - Swing, 20 h.p.
  - Crowd, 13 h.p.
- Control
  - Partial rheostatic.

Operation

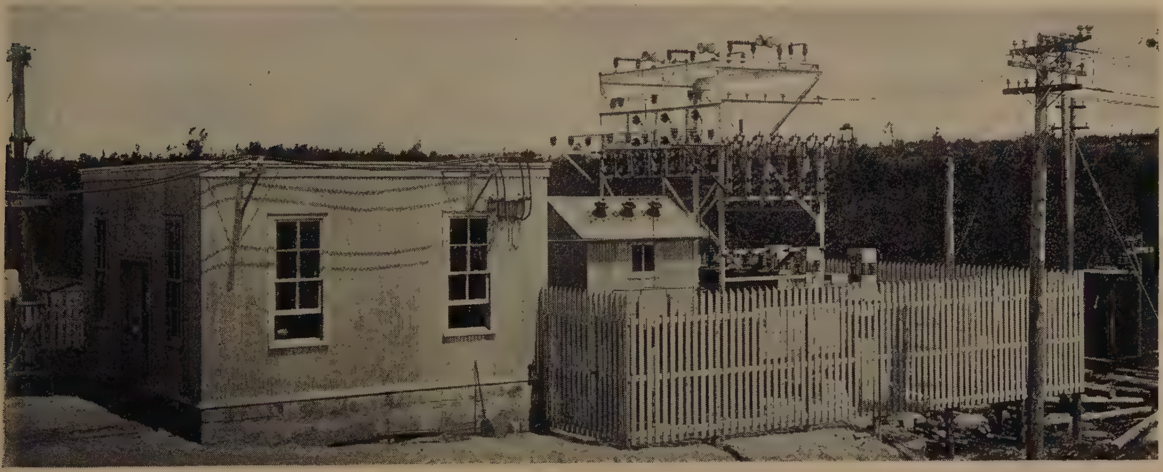

Fig. 15. Substation of the M. A. Hanna Company at the Wabigon Mine

In the field-control system, motor damage during "stalling" is automatically prevented by having the generators differentially wound, so that in the event of the dipper striking an obstruction and causing an increased demand on the generator, the voltage drops. Maximum torque, however, is maintained by the motors. In this system the combined motor and generator characteristic very closely resembles that of the steam shovel. The advantage of eliminating all losses in resistances, having no complicated contactors, having a control that is exceptionally smooth over the widest range of duty, the possibility of automatically correcting the power-factor, and of using regenerative braking on the hoist, have in practice proved the electric shovel to be far superior to the steam machine.

Savings Effected by Electric Shovel (350-ton class) in Comparison with Steam Machine

Labor

The electric shovel has eliminated firemen and craners, and the expense of handling coal as well as the installation and maintenance of water lines. (Electric shovels can be used in places where it would be practically impossible to supply coal to a steam machine.)

Power Cost

The power cost has averaged approximately one-half cent per cubic yard as compared with two and one-half cents per cubic yard fuel cost for the steam machines.

Repairs and Maintenance

Records kept over a period of four years show an average of less than $5000 per year for the 350-ton electric machines, as compared with about $25,000 per year for the steam. These figures are based on a directly comparable yardage. Delays directly chargeable to electric equipment have been less than one per cent of the available working time.

Capacity

Experience has shown that the large, full-revolving electric shovel has a capacity equal to that of the fastest steam machines. Daily runs of 8000 cu. yd. in 20 hours have been recorded, and monthly averages of 150,000 cu. yd. Over long periods, the electric machine will show greater capacity than the steam on account of a higher percentage of actual working time due to fewer breakdowns and no delays for boiler washing and repairs.

Electric Locomotives

The steam locomotive which has been developed and standardized for the average pit is a six-wheel switcher, weighing approximately 60 tons on the drivers. It was therefore decided that a 60-ton electric locomotive, of the swivel-truck type, would be the best to supplant the steam equipment. Fig. 16 shows both the steam locomotive and the electric type which has supplanted it. In view of the fact that the tracks in an open pit, and especially on the dumps, are most uneven, it is necessary to have very rugged and at the same time flexible haulage equipment. In this respect the electric locomotive is far superior. Special attention was given to the design of the trucks on the three electric locomotives at the Wabigon and the final design more than complies with all requirements. The truck side frames are made of rolled steel plate four inches in thickness. The openings for journals, equalizers, and springs were cut out of the solid with oxy-acetylene burners. The bolsters are of heavy design and made of cast steel. The truck frame end ties are of special shape, heavy rolled steel. The spring suspension is very flexible and perfectly equalized. The number of bolts has been reduced to the minimum. Since all hauling of loads is up grade, the electric locomotive shows to great advantage; and owing to this inherent characteristic, it is possible to haul an additional car on each train, over and above that hauled by the same weight steam engine. With the electric locomotive shorter in over-all length than the steam, with its tender, it is possible to handle the additional car per train without increasing the length of loading and

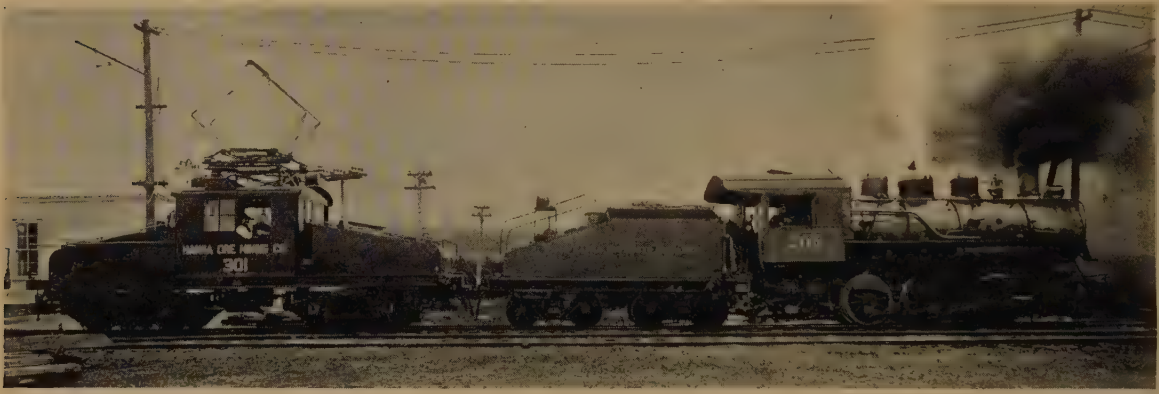

Fig. 16. Type of Electric Locomotive Which Has Replaced the Type of Steam Locomotive Shown

passing tracks. This is graphically explained in Fig. 17.

The principal dimensions and features of the electric locomotives are listed in detail in the Appendix.

Steam Locomotive Costs

Average of Four Months' Operation with 60-ton Steam Locomotives at the Wabigon Mine

Total haul one way, 4000 ft.
Trailing load, 224 tons.
Average grade, 2.1 per cent.
Total coal used, 1311 tons.
Total net ton-miles, 345,800.
Pounds of coal per net ton-mile, 7.59.
Total cost repairs (labor and supplies), $4405.
Repair cost per net ton-mile, $0.012.

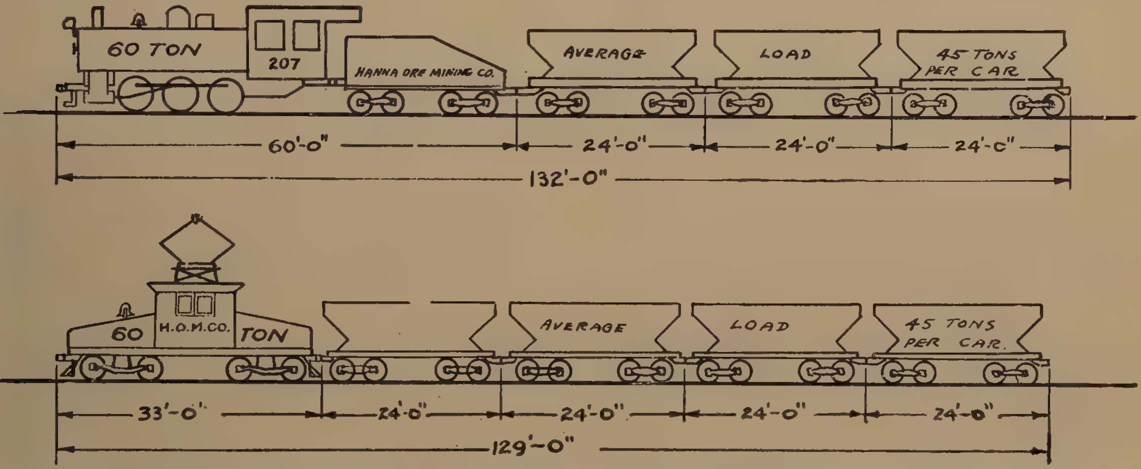

Fig. 17. Diagram Showing Relative Lengths of Steam and Electric Trains. In the upper view a 60-ton steam locomotive is shown hauling three 45-ton ore cars, while the lower view shows a 60-ton electric locomotive hauling four 45-ton ore cars

Average of Five Years' Operation at Another Mine with Similar Haulage Equipment

Trailing load, 178 tons.
Average grade, 2.3 per cent.
Total coal used, 18,363 tons.
Total net ton-miles, 6,595,850.
Pounds of coal per net ton-mile, 5.58.
Cost repairs (labor and supplies), $46,448.
Repair cost per net ton-mile, $0.007.
Minor repairs (other than overhauling) per net ton-mile, $0.002.

The lower coal consumption in the second part of the foregoing table is accounted for by the absence of stops for switch backs, and a lighter trailing load, which permitted higher speeds in moving out of the pit.

Electric Locomotive Costs

Repair Cost

The experience of electrified steam railroads has established a ratio of one to four, to one to eight, in the repair cost of electric equipment as compared with steam. In open-pit work with extremely poor tracks, the repair cost of the electric locomotive is taken as one-fifth that of steam, which is considered conservative.

Minor repairs, other than overhauling, are assumed to be approximately the same for both types of equipment. In the electric locomotives, brush replacements, contactor parts, and other small motor replacements will offset cylinder oils, grate bars, etc.

Power Consumption

The characteristic curves of the motors, and the speed, time, and distance charts form the basis for calculating the power consumption.

Relative Costs of Electric Locomotives as Compared with Steam

Average Stripping Conditions—Operating Three Locomotives

Length of haul (one way), 7000 ft.
Ton-miles per locomotive shift, 1296.
Average grade, 2.2 per cent.

Costs per Locomotive Shift

	Steam	Electric
Labor		
Engineer	$6.50	$6.50
Fireman	5.28	.....
	$11.78	$6.50
Supplies and Maintenance		
Coal at 6.5 lb. per ton-mile	$33.06	.....
Kw-hr. at $0.575 per ton-mile	......	11.62
Minor repairs at $0.002 per ton-mile	2.60	2.60
General repairs at $0.012 per ton-mile	15.60	3.20
Trolley maintenance	......	1.55
Substation maintenance	......	1.05
Total	$63.04	$26.52

Cost of coal delivered in locomotive tender, $7.85 per ton.
Power cost per kw-hr., $0.0156.

Average Ore Loading Conditions—Operating Two Locomotives

Length of haul one way, 7640 ft.
Ton-miles per locomotive shift, 1300.
Average grade, 2.47 per cent.

Cost per Locomotive Shift	Steam	Electric
Labor	$11.78	$6.50
Supplies and Maintenance		
Coal at 7.75 lb. per ton-mile	$29.56	.....
Kw-hr. at $0.394 per ton-mile	.....	12.83
Minor repairs at $0.002 per ton-mile	2.60	2.60
General repairs at $0.012 per ton-mile	15.60	3.12
Trolley maintenance	.....	1.55
Substation maintenance	.....	1.05
Total	$59.54	$27.65

Cost of coal delivered in locomotive tender, $7.85 per ton.
Power cost per kw-hr., $0.0222.

From the figures given, it will be noted that by the use of electric locomotives it is possible to cut the haulage costs more than half.

Conclusion

Since the first electric shovels were put into operation in 1920, there have been 7 more machines installed on the Iron Ranges, consisting of two 350-ton and one 60-ton shovel on the Mesabi Range, and one 350-ton and one 60-ton on the Cuyuna Range. All these machines are fitted with direct-current equipment. There has also been installed one 90-ton and one 40-ton machine on the Mesabi Range fitted with alternating-current equipment. The great field for future development of electrical equipment, as applied to shovels and surface haulage, can be appreciated from a study of Table I, which gives the number of steam shovels and locomotives that are used at the present time by the mining companies on the various ranges in the Lake Superior Region.

APPENDIX

Descriptive Specifications of the 500-volt Electric Locomotives Operating at the Wabigon Mine

General Design

The locomotive is of the swivel-truck type with steeple cab and four direct-current geared motors.

General Dimensions

Length inside knuckles, 37 ft. 4 in.
Height over cab, 12 ft. 0 in.
Overall width, less side collectors, 10 ft. 0 in.
Total wheel base, 24 ft. 3 in.
Rigid wheel base, 6 ft. 0 in.
Track gauge, 4 ft. 8½ in.
Minimum radius of curve, locomotive alone, 150 ft. 0 in.

Weights (Approximately)

Electrical equipment, 22,000 lb.
Air brake and compressor, 5000 lb.
Mechanical equipment, 93,000 lb.
Total weight, 120,000 lb.
Weight on drivers, 120,000 lb.
Weight per driving axle, 30,000 lb.

Running Gear

This consists of two steel-plate-frame side-equalized trucks with rigid bolster. The brakes are inside hung. The frames are tied together at the center and at each end. The springs are of the semi-elliptic and helical types, tempered in oil and proportioned to the weight to be carried with an ample safety factor.

Wheels

The wheels are solid rolled steel, eight per locomotive, 36 in. diameter; tire width, 5½ in.; thickness 2½ in.; tread and flange according to MCB contour.

Axles

The axles are hammered open-hearth steel, having a diameter of 6 in. in the motor bearings and between wheels, except for the wheel gear seat. The journals are of the collar type, 5½ by 10 in., using pedestal type MCB journal boxes.

Foundation

The foundation rigging is properly proportioned to give brake shoe pressure of 85 per cent of the weight of the locomotive with 50 lb. per sq. in. cylinder

TABLE I

State and Range	STEAM SHOVELS				STEAM LOCOMOTIVES			
	35- to 50-ton Class	70-ton Class	90- to 100-ton Class	350-ton Class	60-ton Class	70-ton Class	80-ton Class	100-ton Class
MINNESOTA								
Mesabi	36	86	201	17	67	133	41	25
Cuyuna	1	12	5	..	4	9	..	..
Vermilion	..	2	3	..	..	..	..	..
MICHIGAN								
Marquette	..	15	4	..	4	..	..	..
Gogebic	6	15	19	2	8	7	..	..
Menominee	..	9	5	..	..	..	..	..
Total all ranges	43	139	237	19	83	149	41	25

pressure. The brake shoes are of the standard MCB flange type.

The hand brake is of the ratchet and drop-lever type, provided to hold the locomotive at a standstill.

Platform

The platform is built up of structural-steel longitudinal sills and cast steel. Cast steel and sills are stiffened by brace plates and ⅜-in. steel floor plate securely riveted. Ballast bars are built into the platform in such a way as to give stiffness. Push-pole pockets are provided at each end of the end frames. Three-fourth-inch matched wood floor is provided in the main cab.

Couplers

These are MCB, Sharon, long-shank type with spring draft gear provided; height above rails, 34 in. The coupler housing is attached to the under side of the platform.

Cab

The cab is of sheet steel built up on a structural-steel framework; cab sides and ends ⅛ in. with $\frac{3}{16}$-in. roof. The main cab is 10 ft. long by 9 ft. wide with two sloping end cabs housing the control, each approximately 11 ft. long and 5 ft. wide.

The doors and window sashes are wood, glazed with double-thick clear glass. The doors are located in diagonally opposite corners.

An engineer's seat and arm rest is provided at each control station.

The necessary steps and hand rails are furnished.

Air Compressor

One air compressor is furnished mounted in the cab. The compressor has a total piston displacement of 100 cu. ft. per minute when it is delivering air at a pressure of 130 lb. per sq. in. and operating at 600 volts.

Motors

Four single-gear, commutating-pole, railway motors drive the locomotive; rating 158 amp. at 500 volts. The motor is capable of carrying this rated load for one hour continuously with a temperature rise of 75 deg. C.

They are suspended on the axle and by a motor nose spring connected to the truck bolster.

Gears and Pinions

The gear reduction is 6.13 with an 86-tooth gear and 14-tooth pinion, both of rolled steel. The end pinion is of forged steel and is cut from a solid blank.

Control Equipment

The locomotive is equipped with multiple-unit control, with two control stations arranged for seven steps, two motors in parallel, the two groups in series; and five steps, four motors in parallel. The multiple-unit feature covers only two locomotives.

Rheostats of sufficient capacity for the specified service are provided, being properly secured and insulated.

Contactors of proper size to operate the power circuits are included.

Collecting Device

This consists of a sliding pantograph trolley, mounted on the cab roof over the center line of the track. The trolley, arranged for air release, is raised by springs and lowered by air. The maximum vertical range of the trolley wire is from 17 ft. to 24 ft. above the rail head with standard clearance at 22 ft. Two air valves are provided for controlling the pantograph trolley.

Two special side-arm trolleys are furnished, arranged for a maximum height of wire of 16 ft. 6 in. and a minimum height of 13 ft. 6 in.; normal height being 15 ft. above the rail head. Side trolley wires are located 10 ft. from the center line of the track on either side.

One 500-volt electric cable reel equipment is provided. This is mounted on top of one auxiliary cab and arranged for paying out the cable in either direction. A reel is furnished with 500 ft. of No. 2/0 rubber-covered cable.

The transfer of power from the cable reel to the trolleys is accomplished by means of control switches.

Capacity

The rating of the motors in the locomotive is 75 deg. C. rise by thermometer, in one hour, 158 amp. per motor, 632 amp. per locomotive; volts per motor and volts line 500. The total tractive effort in pounds per locomotive is 17,600. The corresponding speed is 8.0 m.p.h.

The maximum speed of the locomotive on level tangent track is approximately 13 m.p.h. with a train of 540 tons including the locomotive, assuming 10 lb. per ton resistance and 500 volts line.

With a tractive effort of 23,800 lb., the locomotive is capable of hauling a 340-ton train, including the locomotive, up a 3-per cent grade on a tangent track, at a speed of 7.5 m.p.h.

With a tractive effort of 30,000 lb. the locomotive is capable of hauling a maximum train of 340 tons, including the locomotive, up a 3-per cent grade on a tangent track, accelerating at the rate of approximately 0.02 m.p.h.p.s., assuming 10 lb. per ton train friction.

With a tractive effort of 24,000 lb., the locomotive is capable of hauling a maximum train of 600 tons, including the locomotive, on level tangent track, accelerating at the rate of approximately 0.3 m.p.h.p.s., assuming 10 lb. per ton train friction.

When operating on the electric-cable reel, the locomotive is capable of a maximum speed not exceeding 5 m.p.h., the controller not to be advanced beyond the full series position.

The safe coasting speed of the locomotive is 25 m.p.h.

Lighting Equipment

There are the necessary lamps, switches, fuses, and wiring for illuminating the cab and gauges and for headlights. The headlights are built with a 12-in. mirror reflector, focusing device, 94-watt concentrated-filament lamps and steadying resistance. The headlights are mounted on the center of the main cab roof at each end.

The Measurement of Candle-power by Means of the Photo-electric Cell

By F. K. Moss

National Lamp Works of the General Electric Company

The comparatively recent evolution of the electron-tube family has developed a number of members having characteristics as different as those in the members of a human family. For this reason, it is to be expected that they will eventually find application in a wide variety of fields. Already, extensive use has been made of some of them; and new applications of one or another member are being discovered with pleasing frequency. The following article relates to such an application, and describes an investigation made to determine the serviceability of the photo-electric cell to measure the mean spherical candle-power of incandescent lamps. The photometric technique is outlined, the limitations of the application observed, and the results are shown to be distinctly encouraging.—Editor.

Introduction

The measured value of light is one of the few quantities that depends upon the personal judgment of the observer for its determination, and is a quantity that has not been readily obtained with direct-reading instruments. The photo-electric cell offers a means for determining such a quantity and has been made to give satisfactory and consistent results when certain limitations are observed.

In the following discussion the photo-electric cell has been applied only to the measurement of spherical candle-power of incandescent lamps. Even with such a limitation, the scope of the subject is so large that the discussion has been further confined to a consideration of the practical side of the matter and to the actual results obtained, except where some theory and characteristics of the cell are required in the analysis of the results.

ARRANGEMENT OF APPARATUS

Since the integrating photometer has practically replaced the older horizontal photometer, a sphere has been used in conjunction with the photo-electric cell apparatus so that all data and readings obtained are in terms of spherical candle-power. Several methods of using the cell are possible, but the arrangement shown in Fig. 1 is probably the simplest type and has given good results.

The photo-electric cell is mounted approximately at the center of a 60-in. sphere in such a manner that the cell window faces the inner reflecting surface of the sphere. The entire cell is shielded from direct radiation from the test or standard lamp by means of an opaque screen placed between the cell and the lamp. The leads from the cell are carefully insulated at the point where they touch the sphere and are connected as shown in the wiring diagram, Fig. 1. The cell is mounted within the sphere rather than at the aperture merely as a matter of convenience; the most desirable location would be at the aperture of the sphere as the cell would thus not be subjected to heating due to the proximity of the lamp being photometered.

When the reflected light from the surface of the sphere falls upon the cell window, and with the proper potential applied to the terminals of the cell, the galvanometer will show a deflection which depends principally upon the intensity of the illumination on the cell window and the voltage impressed upon the circuit. While this method is of the "direct-deflection type" and not of the "null" or "bridge" type usually employed where sensitive galvanometers are a part of the apparatus, yet the results obtained are well within the accuracy required when the apparatus is properly set up. No amplification of the cell current is necessary.

Using a sensitive galvanometer and a scale mounted at some distance, the deflections obtained were easily read even for minute changes of current flowing in the circuit. The distance of the scale from the galvanometer permitted the latter to be operated with but a few degrees of deflection; hence, the galvanometer suspensions were not subjected to any appreciable twisting moment, which resulted in a uniform and consistent operation of the instrument. No attempt was made to keep the galvanometer reading on a fixed zero from reading to reading, although the "zero" position remained quite constant even after a large number of observations had been taken.

Details of Apparatus

The Photo-electric Cell

The cell used in all tests was of the potassium-hydride type, which is generally considered the best type of cell that can be obtained for work of this nature. A sketch of the cell giving details of its construction is shown in Fig. 2.

The Circuit

All connections were insulated with cambric tubing as it was found that extremely variable results would be obtained if the insulation was poor in quality. This feature is especially pronounced when moisture is present in quantity in the air. Any size wire may be used as resistance is of little consequence in the circuit.

The Galvanometer

A Leeds & Northrup galvanometer was used and this instrument fitted with a concave mirror and a special damping coil consisting of a single turn of copper wire attached to the coil of the instrument. This addition to the instrument was necessary to damp the galvanometer so that readings could be taken with reasonable speed. Using such a winding, the galvanometer became almost deadbeat for relatively small changes in deflection.

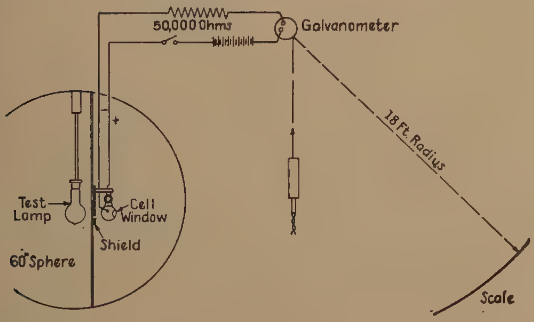

Fig. 1. Arrangement of Apparatus for Measuring Candle-power by Means of the Photo-electric Cell

The Scale

The scale was mounted at a distance of 18 feet from the galvanometer and divided into decimal divisions of which the smallest was about a tenth of an inch. With such a radius it is useless to divide the scale into smaller divisions as the estimating of a half of the smallest division gives a scale with a possible accuracy well within the experimental error of the method as a whole. A scale with a radius less than that used is possible but the larger one facilitates reading.

The Batteries

Small storage batteries of 4.5-amp.-hr. capacity were used to supply voltage to the photo-electric cell. A sufficient number of cells were used so that any voltage from 2 to 200 volts could be obtained in steps of two volts. Spring clips provided a simple and quick means of regulating the voltage impressed upon the cell.

The Resistance Coil

A resistance coil of approximately 50,000 ohms was placed in series with the photo-electric cell to prevent an excess of current from flowing through and damaging the cell in case too great a voltage was applied.

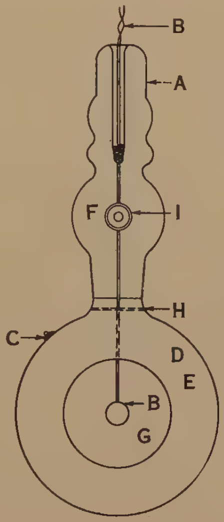

Fig. 2. Sketch of the Photo-electric Cell Used in Making the Measurements

A—Glass bulb
B—Positive terminal
C—Negative terminal
D—Silvered inside
E—Layer of potassium on silver
F—Argon
G—Cell window
H—Deflector
I—Tubulated and sealed

DETERMINATION OF CHARACTERISTICS OF CELL

Before proceeding with the actual candle-power measurement of lamps, it is necessary to investigate some of the more important qualities of the cell and its limitations. The following characteristics should be determined:

(a) Sensitivity to radiant energy.
(b) Response of cell to incident radiation.
(c) Selectivity to certain wavelengths as compared to the eye.
(d) Duplication of readings.
(e) Life of cell, effect of temperature, dark currents, etc.

(a) Sensitivity

The potassium cell is one of the most sensitive of all the numerous types of cells that have been designed. Unlike the selenium cell, it is for all practical purposes instantaneous in operation which is a most important characteristic in its favor.

The response that will be obtained for a given illumination on the cell window is a function of the impressed voltage, and a wide variation in current flowing through the circuit is possible by changing the voltage. The limit, however, is reached at approximately 200 to 250 volts as the cell will commence to "glow" if the voltage is increased beyond this value. The curves in Fig. 3 show the variation in galvanometer deflection with impressed voltage for several different intensities of light. These curves are evidently a part of a family of curves depending upon the intensity of illumination on the cell. From them it is evident that it is desirable to operate the cell at as low a voltage as possible, since the lower the voltage the less will be the possible error due to any fluctuation of voltage.

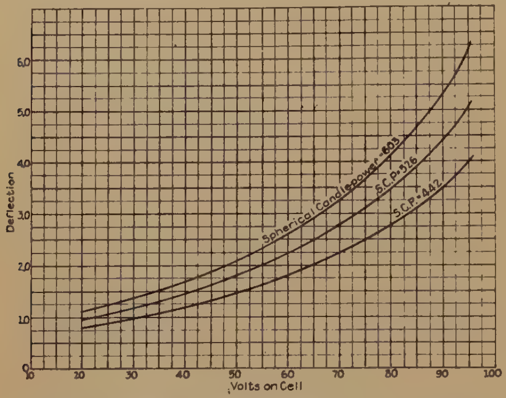

Fig. 3. Impressed Voltage-deflection Curves. 500-watt Mazda C lamps used as light source. $D = ae^{bV}$ where D = galvanometer deflection and V = impressed volts

From actual experiments it was found that a change of less than 0.1 of one per cent in candle-power (computed from a change of 0.02 or 0.03 in voltage) could be detected by the apparatus used. The cell is therefore more sensitive than would actually be required for photometric measurements.

(b) Proof That the Cell Gives Responses Proportional to Incident Radiation

Having obtained a cell of sufficient sensitivity, it is essential that the cell produce responses which are directly proportional to the quantity of light falling upon the cell window. A cell that would not meet this requirement would be valueless for lamp photometry. The response characteristic was determined by selecting a number of lamps of widely differing candle-powers but all of which were rated at the same watts per spherical candle-power. The lamps were rated for spherical candle-power as accurately as was practical by precision methods of optical photometry and these ratings regarded as the "true" candle-power. Owing to certain requirements necessary for the "standard lamps" used in the photo-electric cell method, it was not convenient to use the same group of standard lamps for both the cell and the optical methods. This subject is referred to later.

The lamps were placed in the sphere and set at their rated voltage by means of a potentiometer, and then photo-electric cell readings taken. Plotting the deflection of the galvanometer against the candle-power of the lamps produces a straight line curve, showing that the response given by the cell, for the candle-power range considered, is directly proportional to the incident radiation. These data have been plotted in Fig. 4.

It is interesting to note that the same result is obtained by using a single lamp and varying the voltage impressed upon the lamp to produce the candle-power range desired. Plotting the deflection against the "true candle-power" again gives a straight line over the range considered as shown in Fig. 5. In this test the lamp is burned at different efficiencies for each point obtained.

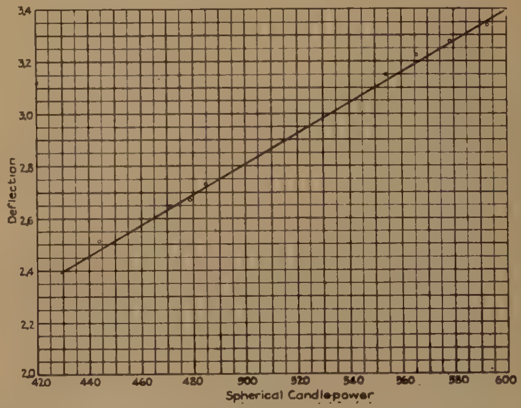

Fig. 4. Candle-power-deflection Curve. 500-watt Mazda C Lamps. Lumens per watt = 15.0. Deflection plotted vs. true candle-power

(c) Selectivity of the Potassium-hydride Cell

The selectivity to certain wavelengths is a most important characteristic of the cell if lamps of different filament temperatures are to be read with one set of standard lamps.

As the optical standard of candle-power is the average effect produced by all wavelengths of the visible spectrum, any instrument used to measure light must do so in such a manner that the readings obtained will agree exactly with the measurements taken by the eye. It is in this respect that the photo-electric cell does not fulfill the requirements of such an instrument as completely as could be desired. The cell has its maximum sensitivity in the blue-violet part of the spectrum and the eye its maximum in the yellow-green portion. Again, the sensitivity of the cell decreases with increasing wavelength and becomes practically zero in the red end of the spectrum. The sensitivity of the cell and the sensibility of the eye to certain wavelengths are as shown in Fig. 6.

While the two curves are far from even approaching similarity, yet in actual practice lamps of the same type will not vary over wide ranges of wavelengths of emitted light. It is possible then to obtain accurate readings with the cell when working within limits of filament temperature that do not vary over a few per cent, plus or minus, from that of the standard lamps. In cases where the color of the lamps to be measured is considerably different from that of the standards, it is possible to apply corrections to the readings and materially decrease the error resulting from color difference.

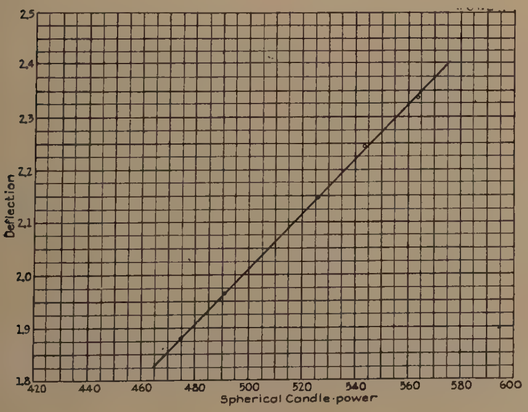

Fig. 5. Candle-power-deflection Curve. A 500-watt lamp burned at several voltages gave the candle-power range

(d) Duplication of Readings

The question of the aging effect upon the cell has always been of importance in work of this kind. Experiment has shown that the particular cell used in this test did not change in character over the six months' period of test. It is possible that the sensitivity gradually decreases with age but this is not an important factor as the decrease in sensitivity can be counter-balanced by an increase of impressed voltage. The tabulations included in this article indicate the precision with which the cell repeats its readings from test to test.

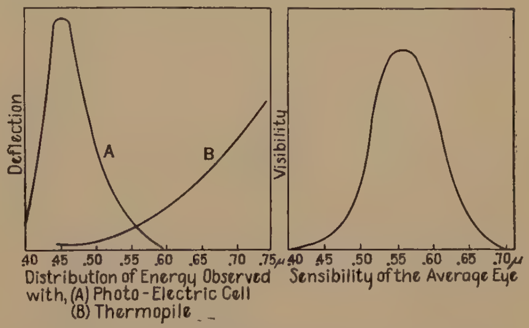

Fig. 6. Response of the Photo-electric Cell, Thermopile, and Average Eye to Radiant Energy Within the Visible Spectrum

(*Curves from Bureau of Standards, Scientific Paper No. 319*)

(e) Effect of Temperature and Dark Currents

The temperature of the cell is a factor that must be considered if it changes during the time in which observations are taken. The absolute temperature is of no importance as the method is merely a comparison between standards and lamps of unknown candle-powers, and if the temperature remains constant the readings can be checked almost exactly. If the temperature gradually increases, which can be noted by a gradual increase of deflection for a given lamp, the deflections will be in error by an amount that is a function of the time between readings. When such conditions prevail the error can easily and accurately be eliminated by taking observations on the group of lamps under test and checking the observations in the reverse order in which they were taken. The average of the two deflections will give deflections that are all based upon the same temperature.

When voltage is impressed upon the circuit but the cell is in darkness, no current should flow through the circuit. The cell used for this test did not permit a flow of current under such a condition.

SPHERICAL CANDLE-POWER MEASUREMENTS BY MEANS OF THE PHOTO-ELECTRIC CELL

Methods

The customary practice in regular photometry of using several standard lamps to fix the candle-power scale has also been followed when working with the photo-electric cell. It is essential that at least two lamps be used as standards but more accurate results can be expected when more than two standards are used to fix the candle-power deflection scale.

The standards required for use in the photo-electric cell method differ somewhat in requirements from those used in optical photometry. In order that an accurate candle-power-deflection curve can be obtained, it is necessary that the standards meet the following specifications:

(a) The type of the standard should be essentially the same as the test lamp to be read.

(b) All standards must be of the same watts per spherical candle-power rating.

(c) The lamps must differ in candle-power so that a curve can be drawn over the range of candle-power that it is desired to read.

The steps involved in taking the data and obtaining the results in terms of spherical candle-power are as follows:

(1) The lamps to be read are arranged in a given order, the standards included, and then placed in the sphere, burned at the proper voltage, and the deflections of the galvanometer noted. After all lamps are rated, the group is again read but in the reverse order and the values obtained averaged for the true deflection. The duplication of the observations is for the purpose of a check and also to correct for any possible "drift" in the cell due to temperature.

(2) Having the deflection for all lamps it is necessary to find the relation between candle-power and deflection. This can be done by plotting the deflections given by the standards against their respective "true spherical candle-power" and drawing an average straight line curve through the plotted points. This straight line, if produced, does not necessarily go through the origin and for this reason it is not possible to establish the spherical candle-power-deflection relation by using but one standard lamp. The more accurate method, and the one that has been used exclusively in all of the included work, is to obtain the equation of the line by the method of least squares. If only four or five standard lamps are used, which is the customary number, the work of obtaining the equation is not laborious.

(3) Once the candle-power-deflection curve or the equation of the curve is obtained, it is a simple matter to solve for the spherical candle-power of the test lamps. A sample set of data and calculations is given in Table I.

The time taken for all operations of obtaining data and computing results is approximately one-tenth of the time taken for work of similar accuracy when done in the usual manner, taking two or three observers and perhaps ten readings per lamp per observer. At present, no estimation can be given comparing the time taken by such a method and methods used in lamp factories where speed is perhaps more important than precision work.

The equation of candle-power and deflection was obtained by using the "true candle-power" of the standards and the corresponding deflections. The results given in Table I (a) show the candle-power of the standards themselves when computed from the equation thus obtained. If all conditions were ideal, the computed results would check exactly from test to test. Actually the results varied slightly as shown. The data are taken from typical tests covering a period of six-months' operation of the same cell. The difference between the "True S.C.P." and the spherical candle-power given by the photo-electric cell is due probably to the usual errors encountered in both the optical and the photo-electric cell methods. These calculations are not intended to show anything else but the fact that the standard lamps used lined themselves up consistently with one another from test to test over a fairly long period of time.

The number of lamps that can be read with one comparison with the standards depends upon several factors such as the accuracy desired and the speed with which the lamps are placed in the sphere and read. Obviously the oftener the lamps are compared with the standard lamps, the greater will be the accuracy expected as the chance of a change in the temperature, galvanometer, or voltage on the cell will be minimized. In work in which precision is required perhaps not more than ten or fifteen lamps should be read for each comparison with the standards.

TABLE I

500-WATT MAZDA C LAMPS

Lamp Number	Lamp Volts	S.C.P.	W.P. S.C.P.	Zero	Deflect. (D)	Diff. (D)	Average (D)	S.C.P. By Cell
				STANDARDS				
7937	100.8	485.2	0.84	340 340	2575 2580	2235 2240	2238	....
6185	109.5	553.9	0.84	340 340	3040 3030	2700 2690	2695	....
6206	119.3	592.4	0.84	340 340	3235 3200	2895 2860	2878	....
6703	93.9	444.2	0.84	340 340	2280 2270	1940 1930	1935	....
		(*)	(*)	TEST LAMPS				(Calculated by formula)
5478	106.7	500	0.90	340 340	2650 2635	2310 2295	2303	498.2
7938	99.2	500	0.82	340 340	2690 2665	2350 2325	2337	503.5
7937	101.3	500	0.82	340 340	2655 2645	2315 2305	2310	499.2
7940	101.7	500	0.84	345 340	2655 2640	2310 2300	2305	498.5
8149	101.8	500	0.80	340 340	2690 2695	2350 2355	2352	505.8

(*) These columns are included so a comparison can be made between the "Calculated" and the "True" candle-powers.

COMPUTATIONS

S.C.P. of Standard	Deflection of Standard	S.C.P. x Deflect.	(Deflection)² (D)
485.2	2238	1,085,877	5,008,644
553.9	2695	1,492,760	7,263,025
592.4	2878	1,704,927	8,282,884
444.2	1935	,859,527	3,744,225
ϵ2075.7	ϵ9746	ϵ5,143,091	ϵ24,298,778

$2075.7 = 4\,a + 9746\,b$** . . . . (1)
$5{,}143{,}091 = 9746\,a + 24{,}298{,}778\,b$ . . . . (2)
$5{,}057{,}443 = 9746\,a + 23{,}746{,}129\,b$ . . . . (1) × 2436.5
$85{,}648 = 552{,}649\,b \quad b = 0.15498 \quad a = 141.3$
S.C.P. $= 141.3 + 0.15498\,D$..(Straight Line Formula)

(**) General Formula.
$\epsilon C.P. = na + b\epsilon D$ (1)
$\epsilon C.P. \times D = a\epsilon D + b\epsilon D^2$ (2)
(a and b are constants)
(n = number of standards)

TABLE I (a)

CONSISTENCY OF THE SPHERICAL CANDLE-POWER-DEFLECTION EQUATION

Lamp Number	"True" S.C.P.	BY PHOTO-ELECTRIC CELL									
		S.C.P. Test 1	S.C.P. Test 2	S.C.P. Test 3	S.C.P. Test 4	S.C.P. Test 5	S.C.P. Test 6	S.C.P. Test 7	S.C.P. Test 8	S.C.P. Test 9	S.C.P. Test 10
7937	485.2	483.5	481.6	482.0	481.5	482.0	480.0	482.0	480.8	482.5	485.6
6185	553.9	556.9	556.5	557.7	556.9	557.7	558.6	556.9	559.1	556.8	555.2
6206	592.4	590.5	591.2	590.4	591.1	590.4	590.0	590.7	589.3	590.8	591.2
6703	444.2	444.6	446.1	445.8	446.3	445.8	447.0	445.8	446.4	445.5	443.9

Tests on 500-watt Mazda C Lamps of *Constant* Watts Per Spherical Candle-power

Five-hundred-watt Mazda C lamps were selected for test purposes because of the stability of such a lamp in maintaining its candle-power and because such lamps can be very accurately standardized.

The results obtained by photo-electric cell measurements on eight 500-watt lamps rated for a uniform efficiency of 0.84 watts per spherical candle are given in Table II.

TABLE II

EIGHT 500-WATT MAZDA C LAMPS. CONSTANT WATTS PER SPHERICAL CANDLE-POWER. READ AGAINST THE SAME FOUR 500-WATT STANDARDS OF TABLE I

W.P. S.C.P.	"True" S.C.P.	S.C.P. BY PHOTO-ELECTRIC CELL		Average Per Cent Error
		Obs. No. 1	Obs. No. 2	
0.84	469	469	468	−0.1
0.84	475	473	470	−0.7
0.84	500	497	498	−0.5
0.84	568	570	570	+0.4
0.84	579	578	577.5	−0.2
0.84	566	560	560	−1.0
0.84	556	562	562	+1.1
0.84	500	496	499	−0.5

Arithmetical Average Error = 0.6%
Algebraic Average Error = 0.2%

From this table it is evident that the cell can be made to give readings that compare very favorably with those obtained by optical photometry when the lamps are burning at the same efficiency as that of the standards against which they are compared. It will be noted that the readings vary plus and minus from what is considered as the "true" candle-power. The error or discrepancy between the two sets of data can easily be accounted for by the experimental error present in the methods of both the photo-electric cell and optical photometry. Repeated tests on 500-watt Mazda C lamps have shown that the two methods can be made to check under the foregoing conditions within an average of less than one per cent. The photo-electric-cell readings from test to test will check much closer than one per cent, in fact rarely will such readings differ by as much as one-half of one per cent. The fact that it will repeat its readings is one of the most favorable features of the cell.

Tests on 500-watt Mazda C Lamps of *Variable* Watts Per Spherical Candle-power

When lamps whose efficiencies vary from that of the standards are read, an appreciable error is introduced. This error increases as the efficiency of the lamp under test departs from the efficiency of the standards against which it is compared. The direction of the error, however, is such as would be expected, knowing the selective character of the cell. The spherical candle-power obtained on the lamps with a rating in watts per spherical candle-power numerically lower than that of the standards is high compared with the true value.

The lamps tested were chosen because of the very wide range in watts per spherical candle-power; a range such as shown by these lamps would be uncommon in commercial work. The results obtained under such conditions are shown in Table III, grouped into two sets, one of which includes lamps of any efficiency, and the other only those lamps that do not vary more than a plus or minus six or eight per cent from the standards.

TABLE III

TWELVE 500-WATT MAZDA C LAMPS. VARIABLE WATTS PER SPHERICAL CANDLE-POWER. READ AGAINST THE SAME FOUR 500-WATT STANDARDS OF TABLE I

W.P.S.C.P.	"True" S.C.P.	S.C.P. by Cell	Per Cent Error
VARIATION IN W.P.S.C.P. (Wide)			
0.93	431	421	−2.3
0.87	492	485	−1.4
0.84	500	498.5	−0.3
0.82	500	503.5	+0.7
0.79	531	535	+0.8
0.76	566	575	+1.6
0.72	578	598	+3.5
VARIATION IN W.P.S.C.P. (Narrow)			
0.90	500	497	−0.6
0.84	500	499	−0.2
0.83	500	503	+0.6
0.82	500	503	+0.6
0.80	500	502	+0.4

A comparison between the two groups will give an indication of the extreme range used in the first case.

The effect of efficiency, or in reality, of color upon the accuracy of the readings can be shown in a different manner using but one lamp. By burning this lamp at several different voltages, a series of readings in candle-power and deflection can be obtained and these are shown plotted in Fig. 7. The one line represents the candle-power-deflection relation as determined by the same four 500-watt standards which it will be remembered have different spherical candle-power values but the same efficiency.

As the candle-power increases with increasing voltage, the efficiency also is increased and the readings will be in error at all points except those whose efficiency is the same or approximately the same as that of the standards. Although the points along the curve are at different efficiencies, the plot is a straight line when the true candle-powers are used, but in order that the cell produce the true candle-power, the efficiencies of the test lamps and the standard lamps must be practically the same. The slope of this line differs between lamps probably due to a difference in gas, filament temperature, and other variables in lamp construction. From Fig. 7 it is obvious that no one candle-power-deflection curve could be found that would give correct readings for all values of candle-power at any efficiency.

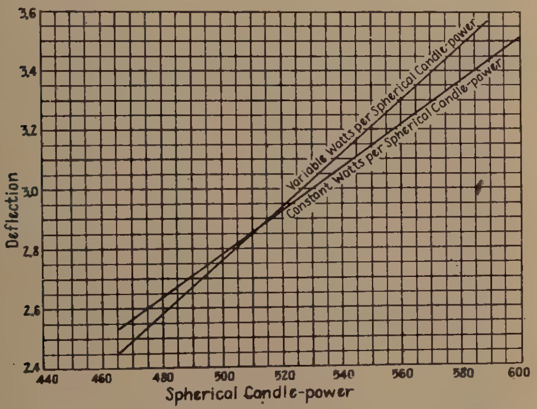

Fig. 7. Candle-power-deflection Curves for Constant and Variable Frequencies

The accuracy with which a lamp can be read without corrections of any kind is, therefore, a function of the efficiency at which the test lamp is read compared to the efficiency of the standards.

As far as the present tests indicate, it appears that the difference between the watts per spherical candle-power on the standard and on the test lamps can be greater for Mazda B lamps than for Mazda C lamps for the same error in spherical candle-power. Table IV indicates the precision with which lamps of the former type can be read.

It records a group of lamps burned at different efficiencies. The results for Mazda B lamps are very good both as to checking the true values of candle-power and also as to consistency from test to test.

CORRECTION OF ERROR PRODUCED BY NON-UNIFORM EFFICIENCIES

Even when the test lamp has an efficiency showing a marked difference from that of the standards, it is possible to obtain very good results by applying corrections. The fact that the cell will give consistent readings even if in error makes such a method possible.

Correction by Filters

Since the sensitivity curve of the cell and the sensibility curve of the eye do not coincide, anything that can be done to reduce the discrepancy between them will aid in decreasing the error. As the cell has a maximum sensitivity in the blue-violet end of the spectrum and since such wavelengths do not affect the eye to a great extent, the insertion of proper color screens in front of the cell

TABLE IV

40-WATT MAZDA B LAMPS AT VARIOUS WATTS PER SPHERICAL CANDLE-POWER. READ AGAINST FIVE 40-WATT MAZDA B STANDARDS AVERAGING 1.40 W.P.S.C.P.

"True" S.C.P. at 112 V.	W.P.S.C.P.	PHOTO-ELECTRIC CELL		"True" S.C.P. at 110 V.	W.P.S.C.P.	PHOTO-ELECTRIC CELL	
		S.C.P.	Per Cent Error			S.C.P.	Per Cent Error
29.08	1.41	28.90	−0.62	27.29	1.45	27.09	−0.72
30.88	1.34	30.74	−0.45	28.98	1.39	28.99	+0.06
29.40	1.40	29.20	−0.68	27.59	1.44	27.44	−0.54
30.47	1.36	30.51	+0.13	28.60	1.40	28.76	+0.56
29.60	1.38	29.75	+0.51	27.78	1.43	27.98	+0.72

Arithmetical Average 0.48

Average 0.52

window will absorb the violet wavelengths and improve the readings. It is not possible to carry this idea of a filter to a nicety with the potassium-hydride cell as the sensitivity curve of this cell does not reach across the visible spectrum and hence no system of filters can be devised that will make the curve of this cell coincide with that of the eye. This coincidence would be possible if there were available a cell that would respond to all wavelengths of the visible spectrum.

The use of a red filter screen produces an improvement in results when the differences in efficiencies are small, but with wide variations the results while slightly better are not satisfactory.

Arithmetical Correction

The manner in which the computed results vary from the true values suggests a possibility of correcting arithmetically for the effect of efficiency. Accordingly, a number of lamps of differing efficiencies were read with the cell, using standards of the same efficiency, and the spherical candle-power of each lamp computed. From the computed and true spherical candle-power, the percentage error can be obtained. The efficiency at which each lamp was operated was obtained from the measured watts and computed candle-power, and might be termed the "pseudo-efficiency" as the candle-power used in obtaining it was not the true candle-power but that obtained by the photo-electric cell and is in error due to the factor of efficiency. Plotting the "pseudo-efficiency" against the per cent error of respective lamps produces the curve shown in Fig. 8 which may be used as a correction curve. As the curve given has been obtained from a relatively few lamps, it is to be regarded only as an approximation.

Table V gives data on seven lamps of different efficiencies showing the "true" spherical candle-power, the spherical candle-power obtained with the photo-electric cell, and the latter values corrected according to the curve in Fig. 8.

While the watts per spherical candle-power percentage-error curve is not absolutely exact due to the variation between individual lamps that cannot be eliminated, it can be relied upon to correct the original readings to less than one per cent in a great majority of cases. Checking better than one-half of one per cent in photometric work on individual lamps is largely a matter of coincidence, as the experimental errors could easily combine to produce such a difference.

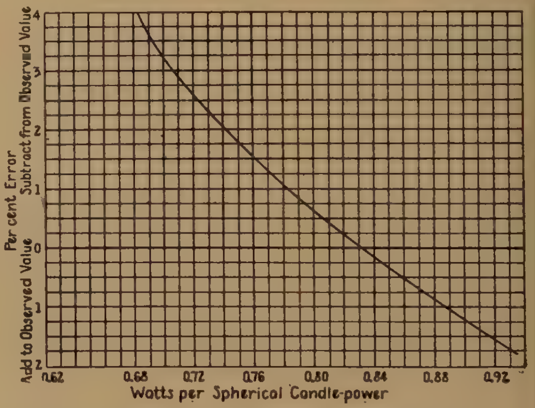

Fig. 8. Correction Curve. Based on standards at 0.84 watts per spherical candle-power. Spherical candle-power used in computations obtained from photo-electric cell

Such a method of reading and correcting the reading would enable photo-electric cell observations to be taken without regard to color difference. While no data have been taken for the express purpose of proving

TABLE V

500-WATT LAMPS, VARIABLE WATTS PER SPHERICAL CANDLE POWER, CORRECTED, USING CURVE IN FIG. 8

Lamp Number	Watts	"True" S.C.P.	W.P.S.C.P.	PHOTO-ELECTRIC-CELL METHOD				
				S.C.P.	Per Cent Error	W.P.S.C.P. (Pseudo-eff.)	S.C.P. Corrected	Per Cent Error
5748	450	500	0.90	492	−1.6	0.915	499.0	−0.2
7940	420	500	0.84	495	−1.0	0.849	496.5	−0.7
8154	415	500	0.83	495	−1.0	0.839	495.5	−0.9
6746	374	435	0.86	428	−1.6	0.874	431.2	−0.9
6889	416	562	0.74	577	+2.7	0.721	562.0	0.0
5497	488	561	0.87	555	−1.1	0.879	559.5	−0.3
8149	400	500	0.80	506	+1.2	0.791	501.7	+0.3

that the correction curve would remain constant over a period of time, the fact that the cell has read a number of lamps over a considerable period of time and obtained the same results shows it is unlikely that the shape of the correction curve would materially change with the age of the cell.

RATING LAMPS AT UNIFORM EFFICIENCIES

An alternative for the correction method and one that would produce good results would consist in reading all test lamps at exactly the same efficiencies as that of the standards. This could be accomplished in actual practice by first obtaining the spherical candle-power-deflection curve of the standards and then adjusting the voltage of each test lamp so that the watts per spherical candle-power obtained would be equal to the value at which the standards are operated. The method of finding the proper voltage at which to set the test lamps would be the same as that already used in regular photometry. This method, while the more accurate, would take considerably more time than the correction method and would be justified only where precision results were required.

MAINTENANCE OF CANDLE-POWER BY THE PHOTO-ELECTRIC CELL

The photo-electric cell offers an excellent means for the maintenance of standards of candle-power. After the initial spherical candle-power values have been obtained from the Bureau of Standards or some other precision laboratory, observations could be taken with the cell and the difference between the cell candle-power and true candle-power could be regarded as a constant. Upon reading the lamps at any other time by means of the photo-electric cell, the constant could be applied to the reading and very accurate knowledge of the candle-power of the lamp would result. A very slight error is introduced by this method due to the fact that the percentage change that occurs in the spherical candle-power of the lamp does not affect the "constant," which must be considered as fixed. However, this error even for large changes in candle-power is not of importance and can be neglected without an appreciable inaccuracy.

CONCLUSION

The reading of spherical candle-power by means of a photo-electric cell is entirely possible and practicable, at least in precision work where the proper precautions are taken to keep experimental errors to a minimum. These tests suggest further experimental work on various types and sizes of incandescent lamps to determine the degree of practicability of its use in the laboratory.

A New Electrically Driven Flooring Plant

By E. B. Clement

Jackson Office, General Electric Company

One of the superior features of electric drive is its lack of dependence on size for efficient application. Whether the task be that of driving a huge rolling mill or making the wheels go 'round in a clock, the electric motor can be suitably proportioned to do the work economically. The following article describes an application of an intermediate size, and is of particular interest because it shows how the combination of central station service and carefully selected equipment of the latest design make an ideal manufacturing unit.—Editor.

To one acquainted with the timber resources of Michigan's Southern Peninsula it might occur that Cadillac is not an ideal location for a large capacity flooring mill, practically the entire output of which is hard maple flooring. It is true that nearly all of lower Michigan's timber used in the manufacture of this product has been exhausted; but due to the necessity of part of Wisconsin's and upper Michigan's lumber passing through lower Michigan to reach the eastern markets, and to the fact that railroads connecting with these eastern markets have a suitable freight rate for "milling enroute," Cadillac appears to be advantageously located for the venture under discussion.

The Mitchell Brothers Company, pioneers in lumbering and the manufacture of flooring, about two years ago found themselves without further timber resources and a completely equipped six-unit flooring plant on their hands at Jennings, Michigan, where railroad facilities were none too good. The demand for "Rockhard" maple flooring, which had won for itself an enviable reputation, continued to grow, necessitating the operation of the old plant with its inadequate shipping facilities or the building of a new plant at a more advantageous location. Consequently it was decided to locate at Cadillac, which is served by the Ann Arbor and Pennsylvania Railroads, tapping Wisconsin's timber lands at the west and upper Michigan's at the north and connecting with through routes to the east.

The new location is on a belt line owned jointly so that shipping facilities are the best obtainable. As a matter of interest, it might be well to mention that transferring operations to Cadillac was not the whole problem, as approximately 60 of the workmen's homes in Jennings were owned by the Mitchell Brothers Company and it was decided to move these also, a distance of about 12 miles.

The new main building is of brick construction, two stories high, with tapestry brick facing and steel trussed roofs. The first floor is devoted to a stock room for the finished flooring, shipping docks, and commercial work; the second floor to the machine room and sorting racks.

The rough lumber after arriving on the railroad siding is unloaded and graded, then reloaded onto kiln cars where it is stored. It is not handled again until it is put through the edging saws, thereby cutting the handling charge to a minimum. From the storage tracks, which will eventually be under cover and of which 2,000,000 board-feet capacity is provided, the loaded cars are put in the kilns where the lumber undergoes a seven-day kiln-drying process.

The kilns are of brick and concrete construction and occupy a building 110 by 170 ft. They consist of four units of the double-track type and two units of the single-track type. The steam for drying is furnished by a boiler plant that for fuel utilizes the plant refuse (such as shavings and sawdust) because most of the wood which can be used for domestic consumption is saved for that purpose. The kiln capacity when fully loaded is 400,000 board-feet of 1-in. lumber.

The drying process is more or less a continuous operation, cars of air-dried lumber being pushed in at one end and kiln-dried lumber being taken out at the other end. One unique feature of the kiln-drying process is that all lumber contains an equal moisture content before the drying begins, for during its travel through the first portion of the kilns it is subjected to a bath of saturated steam which saturates the lumber to its capacity.

After the lumber has gone through the drying process it is shunted on the kiln cars down one of ten tracks to a cooling room where it is allowed to remain approximately 48 hours before being taken to the machine room. In cooling, the lumber absorbs a small percentage of moisture which is beneficial both from the standpoint of machining and the elimination of checking, after the flooring has been finished, thereby assuring a perfect product.

A transfer car, which operates on a transfer track at right angles to the kiln tracks and which is capable of carrying a kiln car and its load, is used to deliver the lumber to the division of the mill for which it is intended, there being three entrances, two to the flooring department and one to the commercial department.

All flooring is manufactured on the second floor and two lumber lifts are used to elevate the lumber. The machine room is 130 by 180 ft. and except for the dust collecting pipes at the flooring machines and a band resaw, Fig. 1, which is located on one side of the room, nothing projects more than 45 in. above the floor. This overhead clearance made the mounting of electrical control apparatus somewhat different from standard practice but the feature was carefully preserved in order to get proper light, as well as to eliminate obstructions in handling the lumber.

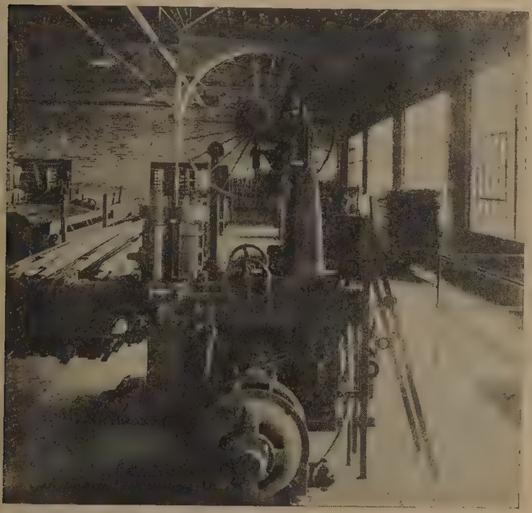

Fig. 1. Motor-driven Band Resaw at Flooring Plant of the Mitchell Brothers Company, Cadillac, Mich.

The whole plant is electrically driven, individual motors being provided for each machine. Every motor is equipped with a starter that furnishes overload protection by means of inverse time-limit relays. Any starter can be disconnected from the line and made dead by means of an enclosed disconnecting switch installed in the line immediately ahead of the device which it is to protect.

The use of fuses for protection of power equipment has been entirely eliminated in this plant, the only use to which they are put being for the protection of branch circuits in order to conform to the Underwriters' requirements.

Magnetic starters, throwing the motors directly on the line, are used on drives up to five horse power. On the squirrel-cage induction motors of larger sizes, hand starting compensators are used.

For the slip-ring type motors, drum controllers are provided for the secondary and a magnetically operated switch with push-button is used in the primary, the first starting point being obtained by pressing the starting button. The controllers and magnetic switches are so interlocked that the operator must bring the controller handle to the OFF position after a shut down, for any reason whatever, before starting again.

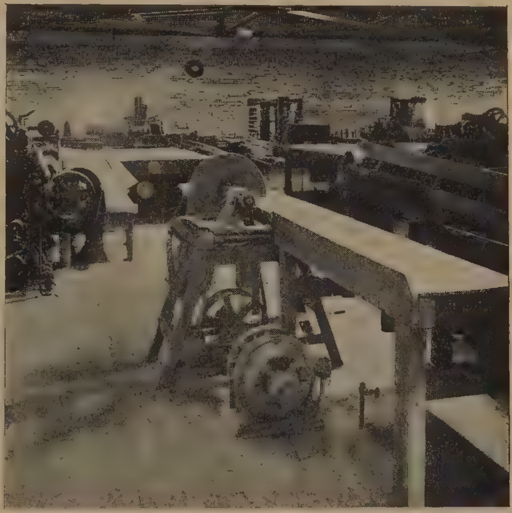

Fig. 2. One of the Cut-off Saws Used to Cut Edgings Unfit for Flooring Into Proper Lengths for Domestic Use

As lumber is being elevated on the lumber lifts, the operation of unloading starts as soon as the top of the load is at a sufficient height to allow the operator to reach the transfer table conveniently. The speed of elevation is arranged to give ample time to have the car unloaded as fast as it is elevated, consequently the operator is always working in a comfortable position.

The transfer table is driven by a 5-h.p. 600-r.p.m. squirrel-cage induction motor, and carries the lumber to an edging saw where it is sawed into the proper widths for flooring. This edging saw is driven by a 30-h.p. 900-r.p.m. squirrel-cage induction motor and lumber passes through at the rate of 140 ft. per minute. The edgings unfit for flooring, which go to make up wood for domestic use, are here taken from the production line and sawed into proper lengths by two cutoff saws, Fig. 2, which are each driven by a 3-h.p. 600-r.p.m. squirrel-cage motor. From these cutoff saws the wood is carried by a motor-driven conveyor to a storage bin, outside of the main plant, which is so arranged that a truck can be driven under it and loaded by means of a trap-door in the bottom of the bin.

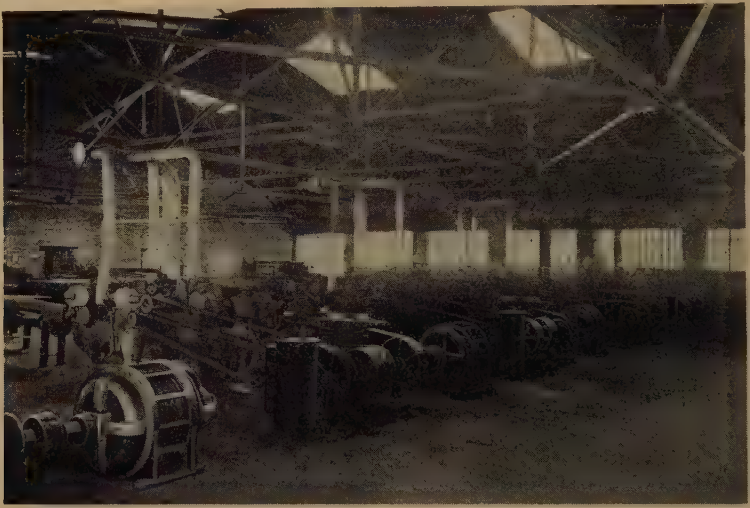

Fig. 3. Battery of Flooring Machines, with Individual Motor Drive, Through Which Lumber Passes at a Rate of About 100 ft. Per Minute

From the edging saws the lumber is pushed on standard mill trucks a distance of about 40 ft. to the flooring machines. There are six of these machines, Fig. 3, each driven by a 75-h.p. 900-r.p.m. slip-ring induction motor. The flooring passes through them at the rate of about 100 ft. per min., and is planed smooth on the top and bottom surfaces and a tongue cut on one side and a groove on the other. In order to conserve floor space, the resistors for use with these motors were mounted directly beneath the controllers and supported on straps from the ceiling of the first floor. As this necessitated bringing all the leads for the different points of control up through the floor to the controllers, a special wiring box was provided which covers the entire back of the controller.

As the flooring leaves the flooring machine, it lands on a transfer table and is transferred to a conveyor which carries it to the tongue end matcher. The conveyor and transfer table are driven by a 5-h.p. 900-r.p.m. squirrel-cage induction motor.

The next operation is to cut out any bad spots and cut a tongue on the end of each individual piece. This operation is performed on an end matcher, Fig. 4, driven by a 10-h.p., 900-r.p.m. squirrel-cage induction motor direct connected.

From the end matcher a transfer table carries the flooring to another conveyor which takes it to the groove end matcher where the unfinished end is trimmed and a groove cut. This second section end matcher, transfer table, and conveyor have electric drives, duplicates of those mentioned for the first line of machines. Each flooring machine, it will be noted, is provided with one end matcher of two sections.

The flooring is now finished and is sorted as to grades and approximate lengths in the machine room, from where it is sent to the assembly room, Fig. 5, for assembling and tying into bundles of different lengths. It is then lowered to the first floor by an electrically driven elevator and either loaded in railroad cars for shipment or placed in the stock room.

From the time the lumber leaves the storage yards it is never exposed to the weather as even the loading into railroad cars is done indoors, Fig. 6.

The output of the plant is expected to average 1,000,000 feet of flooring each month.

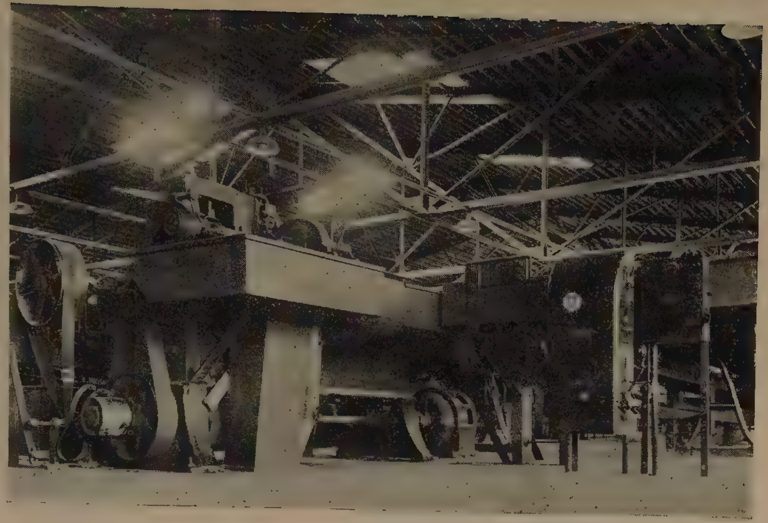

Fig. 4. End-matcher Machine Which Cuts a Tongue in the End of Each Individual Piece. A similar machine cuts a groove in the other end

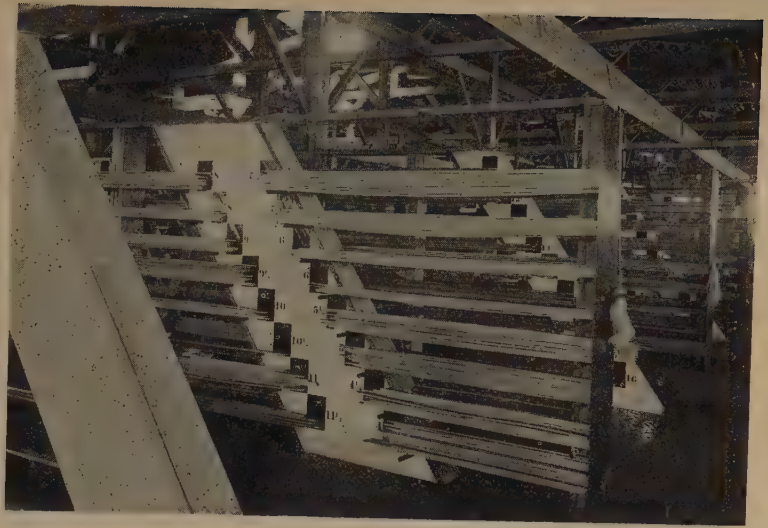

Fig. 5. Assembly Room Where Flooring is Stacked According to Grade and Length Ready for Tying Into Bundles

Fig. 6. Even the Loading Into Railroad Cars is Accomplished Indoors to Protect the Flooring from the Weather

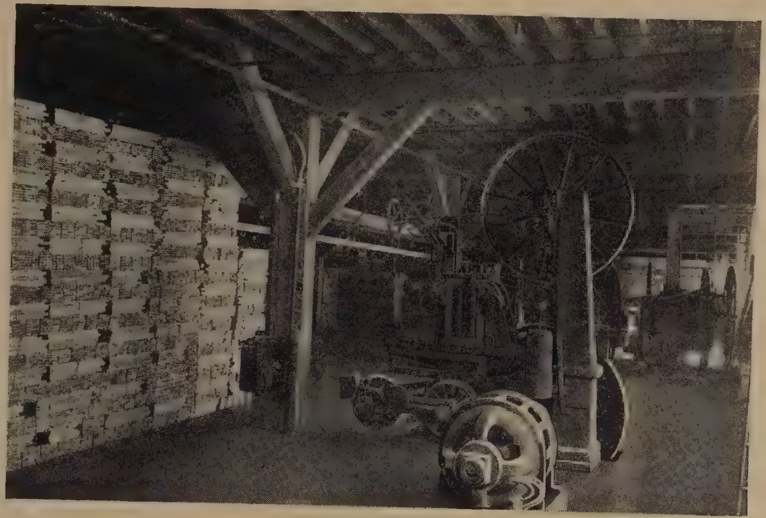

Fig. 7. 52-in. Band Resaw, which with Surfacer (not shown), Comprises the Unit for Commercial Work

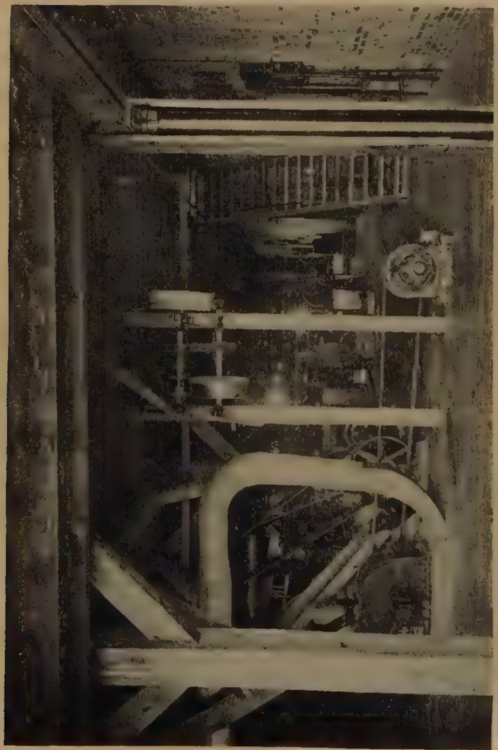

Fig. 8. Motor-driven Machine for Hogging the Edging Before it is Picked up by the Dust-collecting System

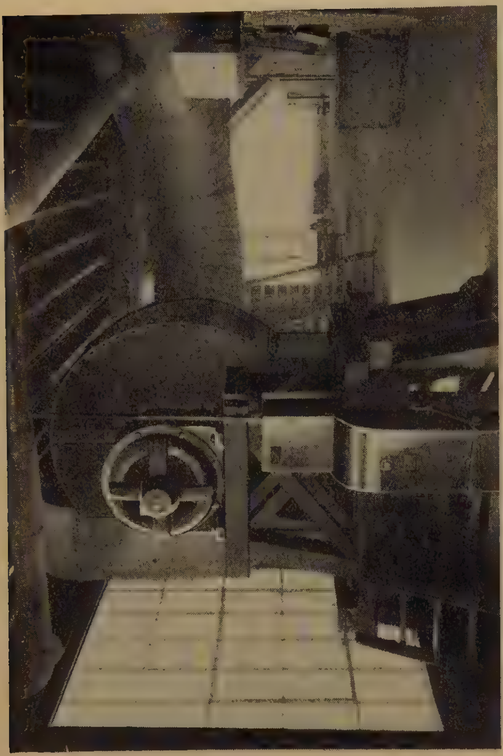

Fig. 9. 60-h.p. Squirrel-cage Motor Driving 90-in. Blower in Dust-collecting Service for Daytime Operation

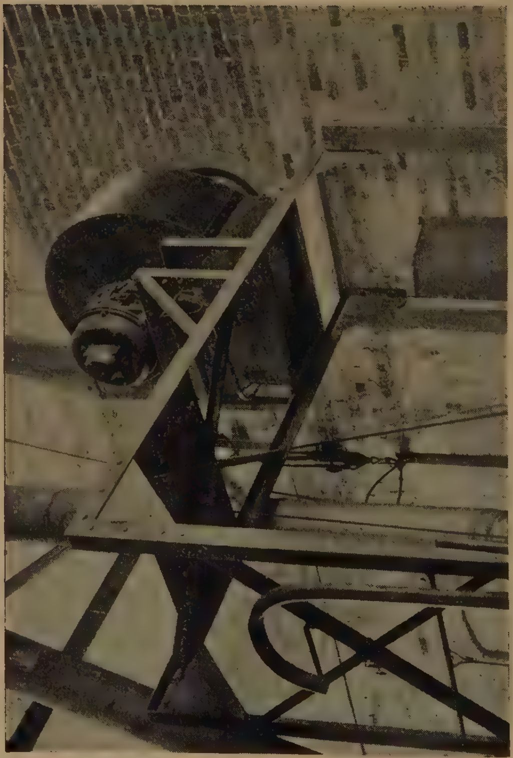

Fig. 10. 10-h.p. Blower for Feeding Refuse from Storage Bins Into Cyclone During Night Operation

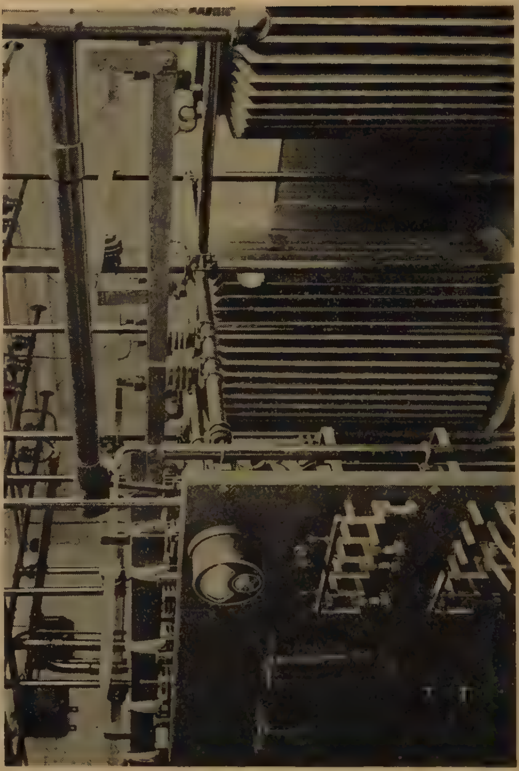

Fig. 11. Substation of the Mitchell Brothers Company Showing General Arrangement

This does not, however, cover the complete electrical installation as there remain the refuse to dispose of and the operation of a unit for commercial work.

For the latter activity there are located on the first floor a 52-in. band resaw, Fig. 7, driven by a 40-h.p. slip-ring motor and a surfacer driven by a 75-h.p. squirrel-cage induction motor.

All large refuse is hogged before being picked up by the dust collecting system; and two hogs, Fig. 8, driven by 20-h.p. slip-ring motors are used for this purpose.

The dust collecting is taken care of by two fans, one 80-in. and the other 90-in., Fig. 9, driven by 50- and 60-h.p. squirrel-cage motors respectively. This covers essentially all of the motor equipment except for the wood and refuse conveyors of which there are five driven by 5- and 10-h.p. 600-r.p.m. squirrel-cage induction motors, the size of motor depending upon the length of the conveyor.

During the day the refuse is blown by the main dust-collecting fans into the cyclone, from which the boilers are fed by gravity. At night a 10-h.p. squirrel-cage motor is used to drive a blower, as shown in Fig. 10, which picks up the refuse from storage bins and blows it into the cyclone, from which it passes to the boilers as in the daytime.

Substation

The electrical substation and boiler room are in a building approximately 60 feet from the main plant. Power is brought in by the Consumers Power Company, at 2400 volts, 3-phase, 30 cycles, and after passing through a high-tension oil circuit breaker is stepped down by three 200-kv-a. transformers to 480 volts. All of the substation equipment, Fig. 11, is located indoors for appearance's sake although the transformers are of the outdoor type.

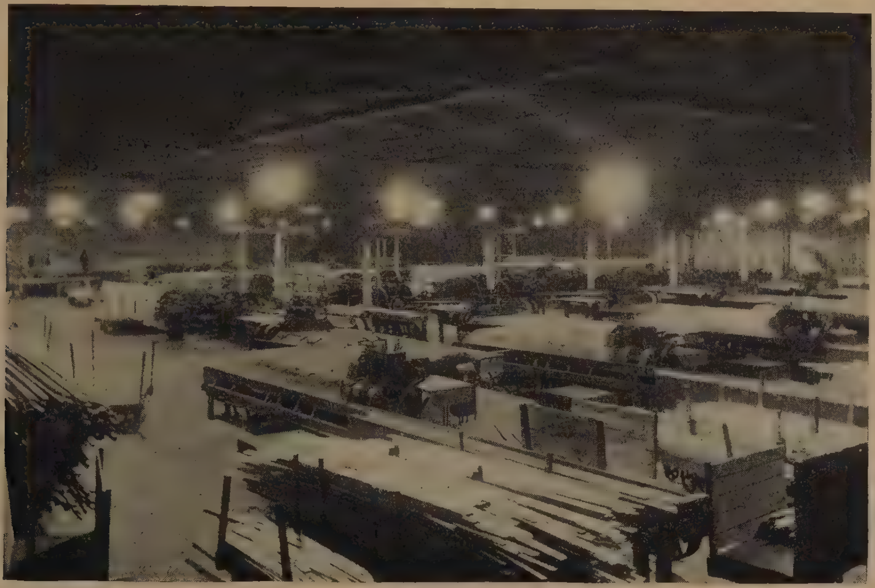

Fig. 12. Main Machine Room (night view) Showing Individual-motor Drive as Applied to the Machines

A 480-volt bus is provided from which four power feeders after passing through oil circuit breakers are taken underground in lead-covered cable encased in fiber conduit to the distribution boxes in the main plant. The fiber conduit is embedded in concrete thereby providing a waterproof feature. The conduits leave the substation through a trench immediately back of the switchboard. The transformer oil drain pipes are all connected together and piped to the end of the trench opposite that from which the cables lead out and this portion of the trench is lined with sheet metal to provide a tank in case it should ever be found necessary to drain the oil from a transformer.

The power transformer bank is connected delta/delta, the delta's being formed by the high- and low-tension busses.

Lighting service is provided by a 25-kw. transformer located in the substation, the low-voltage side being connected for 120/240 volts. This transformer is protected by means of fuses on the high-tension side as it was thought advisable to have the circuits so arranged that the complete power installation could be disconnected without affecting the lighting. Another reason for not connecting this transformer through the main oil circuit breaker was the fact that it would receive practically no protection with a relay setting arranged to protect the power transformers.

A six-circuit lighting feeder panel forms part of the switchboard, from which the current is delivered in the same manner as the power circuits through lead covered cable underground to the main plant.

The machine floor is lighted with sixty 200-watt bowl-enameled lamps, Fig. 12, used in connection with RLM dome reflectors. Yard lighting is taken care of by a line carried through the center on poles which support standard lighting brackets.

An unusual feature regarding the illumination of this plant is that the night watchman will not carry a light of any kind. The wiring is so arranged that by following the route laid out for him he will always by means of three-way switches have light ahead of him.

The electrifying of this plant clearly demonstrates the flexibility of installation of electric drive. Although the bulk of the machinery had originally been built to operate from a line shaft, in the majority of cases it was possible to direct connect the different units to their individual motors.

The complete electrical equipment was installed by the Nelson Beckman Electric Company of Cadillac.

Rectifier Wave Forms

By D. C. Prince

Research Laboratory, General Electric Company.

Various factors influence the output wave form of rectifiers, and a knowledge of how to adjust them properly is essential to obtain the best service from this type of converter. Information to this end is presented in the following article, in which involved mathematics have been purposely avoided. The necessary fundamental formulas are supplemented by simple tables for convenience in calculation.—Editor.

A study of rectifier circuits is primarily a study of wave forms. Unlike rotating apparatus, a rectifier stores no energy within itself so that there is a constant connection between the currents and voltages on the alternating-current side, and the current and voltage on the direct-current side of the rectifier. This is most clearly brought out by assuming ideal conditions. The rectifier is to be fed through a transformer of zero impedance from a sine-wave zero-impedance network.

Fig. 1 represents such an ideal single-phase full-wave rectifier circuit. The rectifiers used are supposed to have no drop and no lag or inverse currents. Energy is supplied to the transformer primary winding T. The secondary winding T' is connected at its ends to the rectifier anodes a and a'. The rectifier cathodes c and c' are connected to the midpoint of the transformer secondary T' through the load resistance R. When anode a is positive with respect to its cathode, a' is negative. Current flows from anode to cathode when the anode is positive, therefore, current flows in the circuit $T'\ a\ c\ R$ to T' again, in the direction of the arrow. There is no drop except in R, so that for the half cycle during which a is positive, Ohm's Law gives the relation between the current through the resistance and the transformer voltage. At the beginning of the half cycle the current is zero; and at the end of the half cycle the current is again zero. During the other half cycle, a' is positive and current flows in the circuit $T'\ a'\ c'\ R\ T'$, and as before, the current and voltage relation follows Ohm's Law. From the primary side the circuit behaves exactly as though the resistance R were connected across one half of the secondary winding T' and there were no rectifiers in circuit. In the secondary the form and magnitude of current and voltage are the same as though no rectifier were present, except that instead of reversing every half cycle the current flows in one direction when it flows at all.

The wave shapes of the primary current and voltage are sinusoidal while the current and voltage through the load R are also sinusoidal for half waves, but are always in the same direction, as shown in Fig. 2. This state of affairs is quite satisfactory in the primary circuit, but is in general not at all satisfactory for the load. The current and voltage in a direct-current circuit should usually contain no periodic pulsations of more than a few per cent in value.

To meet this criticism the rectifier of Fig. 1 may be modified by adding an inductance in the load circuit as shown at L in Fig. 3. If this inductance be large it will prevent any undesirable pulsation of current in load R. As before, the current will flow from a or a' whichever is positive with respect to the other, however the value of that current must be the value established by the inductance, and not a sinusoidally varying current. When current flows it is in the form of a square block, and the primary current must also be in the form of square blocks in order that the total ampere-turns of the transformer primary and secondary may at all times be zero. In other words, neither the transformer nor rectifier store energy and so cannot alter the wave shape.

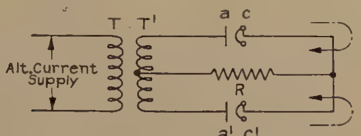

Fig. 1. Ideal Single-phase Full-wave Rectifier Circuit. The rectifiers used are supposed to have no voltage drop and no lag or inverse currents

The primary and secondary voltages and currents now assume the form shown in Fig. 4, e_p and i_p being the primary voltage and current respectively, e_a and $e_{a'}$ the voltages of the two halves of the secondary winding, and e_c the cathode potential with respect to the center of the secondary winding. The latter actually falls upon e_a or $e_{a'}$, whichever is positive, but is shown below for clarity. Current and voltage i_R and e_R in the load are constant, while in the two halves of the secondary winding current flows in square blocks i and i'. A transfer from one to the other takes place while the transformer voltage is passing through zero. The difference between e_c and e_R is the drop across the inductance which stores the inequalities of energy supply.

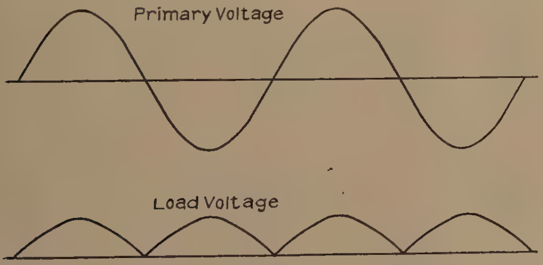

Fig. 2. The Wave Shape of the Primary Voltage is Sinusoidal; while the voltage across the load R, Fig. 1, is also sinusoidal for half waves but always in the same direction

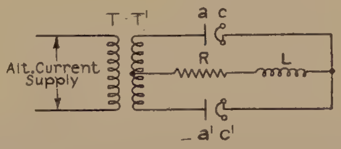

Fig. 3. Rectifier Circuit as Shown in Fig. 1 but Modified by Adding an Inductance L in the Load Circuit

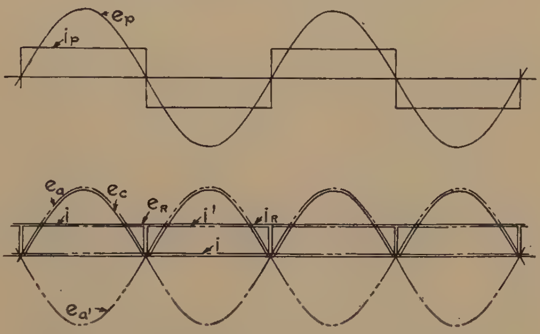

Fig. 4. Primary and Secondary Voltages and Currents of Rectifier Diagrammed in Fig. 3

e_p is the primary voltage. i_p the primary current. e_a and $e_{a'}$ are the voltages of the two halves of the secondary winding. e_c is the cathode potential with respect to the center of the secondary winding. e_R the load voltage. i_R the load current. i and i' are the secondary currents.

We see from the foregoing that we may have either sinusoidal input or steady output in a single-phase rectifier, but we cannot have both. As long as the total rectifier capacity is small compared with other loads on a system, the primary current wave from the rectifier is of little importance and is ignored.

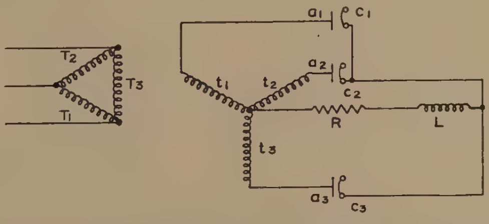

Fig. 5. Circuit Diagram of Three-phase Rectifier

T_1, T_2, and T_3 are the transformer primaries, t_1, t_2, and t_3 the corresponding secondary windings. a_1, a_2, and a_3 the rectifier anodes while the cathodes c_1, c_2, and c_3 are connected together. L is the inductance. R the load resistance.

Before studying the effect of transformer inductance on the ideal case, the corresponding ideal phenomena in polyphase rectifiers will be considered. Fig. 5 is a circuit diagram of a three-phase rectifier. T_1, T_2, and T_3 are the transformer primaries supplied from a three-phase power source, and t_1, t_2, and t_3 are the corresponding secondary windings which are connected to the rectifier anodes a_1, a_2, and a_3. Cathodes c_1, c_2, and c_3 are connected together. From this common point current flows through the inductance L and load resistance R. In Fig. 6-a, i_1'', i_2'', and i_3'' are the blocks of current which flow in the transformer secondary windings t_1, t_2, and t_3 and combine to give the direct current I through the load R. The current I is kept constant by the inductance L. The currents i_1'', i_2'', and i_3'' each contain a direct-current component which cannot be transmitted through a transformer. For this reason the primary transformer currents are as shown in Fig. 6-c. Each current falls above and below the zero axis by an amount to make the positive and negative areas exactly equal. Fig. 6-b is the voltage curve for this rectifier, e_1, e_2, and e_3 being the voltages communicated to anodes a_1, a_2, and a_3 measured from the common point of the secondary windings. Since cathodes c_1, c_2, and c_3 are all at one potential, that potential will be determined by the most positive anode. The curve of cathode potentials is e, while E is the output potential across the load and the difference between E and e is the drop across the inductance L. Fig. 6-d shows the current i in one supply line and is obtained by adding the currents in windings T_1 and T_2. The current in T_2 is reversed as usual in making up the line current from the delta current. The currents in both Figs. 6-c and 6-d show by their dissymmetry the presence of even harmonics.

The currents in any other case may be determined graphically as has just been done in the three-phase case. However, it is shorter to do the work analytically.

It is apparent that there cannot be any unidirectional component of voltage across the inductance L. Therefore the direct voltage E must be the average of the rectified voltage e. The time during which any anode carries current is the complete cycle divided by the number of anodes. The curve e repeats itself for each anode so that it is sufficient to average the rectified voltage over that part of the cycle only. Let p be the number of phases or anodes, then the average rectified voltage expressed in terms of the peak alternating voltage is

$$E = \frac{p \sin \frac{\pi}{p}}{\pi} \qquad (1)^*$$

Table I is an expansion of this formula for several of the more usual numbers of phases.

From formula (1) and Table I the rectified voltage for any rectifier is readily approximated. Certain practical considerations which somewhat alter the result will be discussed later.

The pulsations of the rectified wave e may be described as a series of higher frequency voltages superimposed upon the continuous potential E. The value of these pulsating voltages at any frequency in the ideal case may be determined from the formula

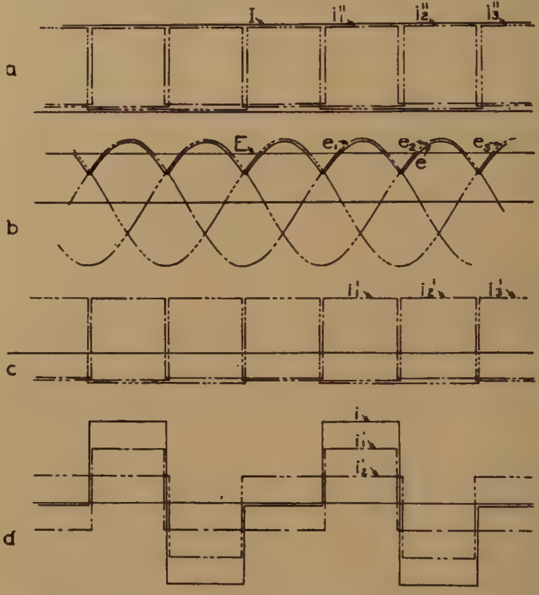

Fig. 6. Primary and Secondary Voltages and Currents of Rectifier Shown in Fig. 5. The currents in both Fig. 6-c and 6-d show by their dissymmetry the presence of even harmonics

(a) i_1'', i_2'', and i_3'' are the currents flowing in the secondary windings. I is the load current.
(b) e_1, e_2, and e_3 are the voltages communicated to the anodes. e is the cathode potential. E the output potential across the load.
(c) i_1', i_2', and i_3' are the primary transformer currents.
(d) i is the current in one supply line.

$$a_n = \frac{2E}{(n^2-1)} \qquad (2)^*$$

$$\frac{a_n}{E} = \frac{2}{(n^2-1)} \qquad (2a)$$

where E is determined by formula (1), and a_n is the maximum value of the voltage pulsation at a frequency n times the frequency of the alternating-current input measured from the average value E and expressed as a fraction of the peak alternating voltage. Table II derived from formula (2a) gives the three lowest frequency pulsation voltages for each of the usual rectifier combinations. The lowest frequency appearing in the rectified voltage is p times the alternating-current frequency, and the others given in the table are two and three times that frequency. The figures in the table are fractions of E by which the pulsating voltages depart in both directions from E.

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*See Appendix for derivation.

These data permit a ready determination of the inductance L required to smooth out the rectified wave. For instance, if a plus-and-minus variation in current of one per cent is permissible in a rectifier supplying 15,000 volts, 2 amp., the permissible current pulsation is 0.02 amp. (peak). From Table II a single-phase rectifier has a double-frequency pulsating voltage of 15,000 × 0.667 or 10,000 volts (peak). The required inductance is then $\frac{10{,}000}{0.02} = 500{,}000$ ohms at 120 cycles or 664 henries. A six-phase rectifier has a pulsating voltage of $15{,}000 \times 0.057 = 855$ volts at 360 cycles. The required inductance is $\frac{855}{0.02} = 42{,}750$ ohms or 19 henries. The impedance of the load is not counted upon so that the result is conservative. The lowest pulsating frequency requires the largest inductance so that the higher frequency pulsations are cared for automatically.

The preceding paragraphs give the analysis of rectifier output voltages. The corresponding input alternating currents can be determined by the same analytical methods. The current drawn by one anode in the ideal case is a square block of duration $\frac{2\pi}{p}$. In terms of sine-wave alternating currents these blocks may be considered as made up of a fundamental-frequency sine wave and a series of multiple-frequency harmonics. Let a_n be the maximum amplitude of the nth harmonic. Then

$$a_n = \frac{2I \sin \frac{n\pi}{p}}{n\pi} \qquad (3)^*$$

Formula (3) may be expanded into a table such as Table III which shows the values of the first seven frequencies using the height of the square block as unity.

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*See Appendix for derivation.

TABLE I
RECTIFIER OUTPUT VOLTAGE

Phases	Average / A-C. Maximum	Average / A-C. Root Mean Sq.
Single-phase (two anodes)	0.636	0.900
Three-phase (three anodes)	0.827	1.170
Quarter-phase (four anodes)	0.900	1.275
Six-phase (six anodes)	0.955	1.350
Infinite phases	1.000	1.41

TABLE II
RECTIFIER VOLTAGE PULSATIONS

Phases	Least Frequency	AMPLITUDE (PEAK)		
		1	2	3
Single-phase (two anodes)	2	0.667	0.133	0.0571
Three-phase (three anodes)	3	0.250	0.057	0.025
Quarter-phase (four anodes)	4	0.133	0.032	0.014
Six-phase (six anodes)	6	0.057	0.014	0.006

TABLE III
HARMONIC COMPOSITION OF RECTIFIER INPUT CURRENTS

Phases (Number of Anodes)	2	3	4	6
Fundamental	0.637	0.552	0.450	0.318
Second harmonic	0.0	0.276	0.318	0.276
Third harmonic	0.212	0.00	0.150	0.212
Fourth harmonic	0.0	0.138	0.0	0.138
Fifth harmonic	0.127	0.110	0.090	0.064
Sixth harmonic	0.0	0.0	0.106	0.0
Seventh harmonic	0.091	0.079	0.064	0.045

All of the harmonic frequencies flow in the transformer secondary windings. In the two-, four-, and six-anode combinations all of the even harmonics of phases displaced 180 electrical degrees are in opposition in the primary and cancel out. In the six-anode arrangement, the third harmonic and all its multiples circulate in the primary delta and do not appear in the supply lines. In this way the higher numbers of phases produce not only a more uniform output, but also have a more nearly sinusoidal input.

There are some disadvantages in using large numbers of phases. The square blocks of current cause more heating than a smooth symmetrical sine wave. To show this Table IV has been drawn up.

The value of amperes given in the first column is the value which can flow for the fraction of a cycle given in the third column and give the same heating as one ampere of sinusoidal alternating-current. The average volts of the second column are determined over the same period that the current flows. Power for a whole cycle is then the product of all three columns. It appears that the three-phase rectifier is most economical of transformer windings.

The advantages of higher numbers of phases can be obtained without sacrifice in transformer capacity by combining groups of smaller numbers of phases. Fig. 7 shows how two three-phase units may be connected in series to secure the advantages in wave form obtainable otherwise only by the six-phase connection.

The windings T_1, T_2, and T_3 are all on one transformer and are so connected that the voltages of the secondary star T_2 are displaced 180 electrical degrees from those in T_3. This causes both output voltages and alternating input currents to be displaced in such a way as to give a resultant the same as with a six-phase connection, although each secondary winding is carrying current one-third of the time.

In case the higher voltage is not desirable, two or more groups may be connected in parallel through an "interphase" transformer. Fig. 8 shows an arrangement of two three-phase units so connected. The interphase transformer *A* is, in this case, a simple auto-transformer having a single winding with a mid-tap. The function of this auto-transformer is to deliver to the load *R* the average of the instantaneous voltages of the two three-phase units. The direct currents flow through the halves of the winding in opposite directions so that there is no direct-current saturation of the auto-transformer core. In the output voltage all even multiples of the fundamental frequency are displaced 180 electrical degrees in the two three-phase units. The average of all these frequencies between the two units is therefore zero, and they are eliminated. The same is true of the input current.*

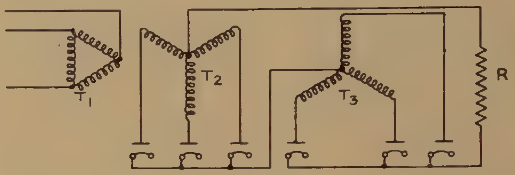

Fig. 7. Method of Connecting Two Three-phase Units in Series to Secure the Advantages in Wave Form Obtainable Otherwise Only by the Six-phase Connection

In the preceding paragraphs of this article an attempt has been made to develop all those relations which are needed in answering the usual questions which come up regarding rectifier circuits. If it is merely desired to determine voltage ratios, approximate wave forms, transformer sizes, etc., the ideal relationships are quite satisfactory. To go further and include the effect of trans-

TABLE IV

TRANSFORMER OUTPUTS WITH VARIOUS NUMBERS OF PHASES BASED ON SECONDARY HEATING

	Amperes	Volts Average	Fraction of Cycle	Power	Per Cent
Non-rectifying	1 (r.m.s.)	10,000 (r.m.s.)		10,000	100
Single-phase	1.41	9,000	0.5	6,370	64
Three-phase	1.73	11,700	0.333	6,750	68
Quarter-phase	2.00	12,750	0.25	6,375	64
Six-phase	2.45	13,500	0.167	5,510	55

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*These statements may be verified by writing out the series which expresses either input current or output voltage and adding or averaging two such series displaced 180 deg. in terms of the fundamental. The signs of the different terms are given in the mathematical derivations in the Appendix.

former inductances does not greatly affect the relationships already developed, but throws light on certain other factors.

A rectifier is usually considered as a device which conducts current in one direction only. However, if any rectifier is already conducting a considerable direct current, it is easy to see that it can also conduct a smaller alternating current superimposed on the direct current. This condition is shown by Fig. 9. The presence of the direct current *I* permits the rectifier to conduct the additional alternating current *i* which is not rectified as long as its peak value is less than *I*. If the peaks of *i* are greater than *I*, the alternating current can still flow unaffected until the instant when *i* momentarily becomes equal to *I*, at which point it is arrested.

Suppose the transformer in Fig. 3 to have inductance. At the time when the impressed voltage passes through zero, suppose that the current has been flowing through *a c* so that this rectifier may be considered as conductive in both directions. The new voltage which begins to rise is in the direction to make current flow in the rectifier *a′ c′*. For the moment then, both rectifiers are conductive and the winding *T′* is short circuited through the two rectifiers in series. An alternating current then starts to flow, the final value of which would be limited only by the impedance of the alternating-current apparatus. This continues to the point where the value of alternating current attempts to exceed the direct current passing through *a c*. At this point the short circuit is interrupted. Referring to Fig. 10, at time t_0 the potential difference between *a* and *a′* reverses and produces the condition in which both rectifiers are conducting. Alternating current *i* then starts to flow just as though it were going to reach full short-circuit value. But at time *t′* the tube *a c* carries no current and becomes non-conducting to currents in the direction in which the voltage is then acting.

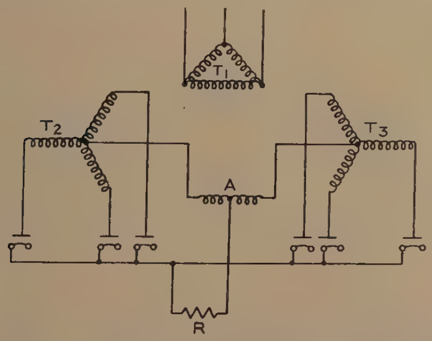

Fig. 8. Arrangement of Two Three-phase Units Connected in Parallel Through an "Inter-phase" Transformer

If the short circuit were not interrupted, the short-circuit current would flow like any short-circuit current, becoming finally symmetrical with respect to the zero axis, as shown by the dotted extension. Its phase is determined by the ratio of resistance to inductance and would normally be almost 90 deg. behind the impressed voltage.

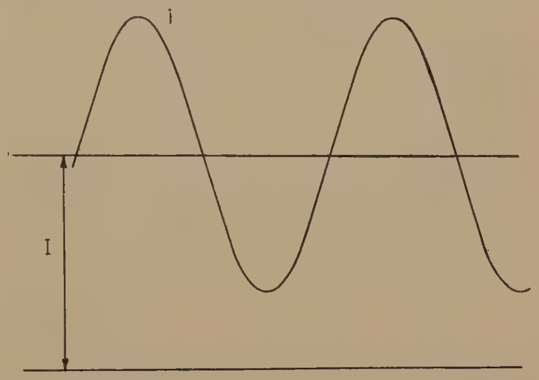

Fig. 9. The Presence of the Direct-current *I* Permits the Rectifier to Conduct the Additional Alternating Current *i*, Which is Not Rectified as Long as Its Peak Value is Less Than *I*

From the fact that the changing current is produced under short-circuit conditions, not only the transformer but the whole supply system impedance is involved. Suppose that under short circuit the peak value of the alternating current is ten times the direct load current then, neglecting resistance, the period from t_0 to t' would occupy approximately 26 deg. of electrical arc, after which the normal conditions of the ideal circuit

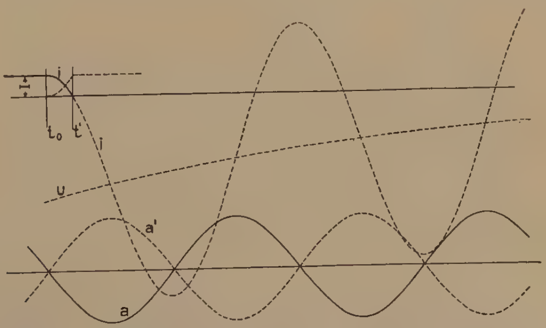

Fig. 10. Graphical Representation of Conditions Arising from the Supposition That the Transformer Shown in Fig. 3 Has Inductance

would be resumed. ($1-\cos 26$ deg $=0.1$ so that a current whose amplitude is ten times normal will reach normal in 26 deg.)

During the 26 deg. of short circuit there is no voltage being produced by the rectifier. The output voltage and current waves are then as shown in Fig. 11. It is seen that the effect of short circuiting the rectifier for a few degrees has been to cut a notch in each voltage wave. The average of the wave will then be less than it was before, and the rectifier output voltage will be reduced. A quantitative investigation along this line faithfully produces the observed voltage regulation of the rectifier. The increased irregularity of the wave places some additional burden upon the smoothing inductance and has a corresponding effect upon the input current wave. Assuming a lap angle of 30 deg. Table V has been prepared to see what the effect of inductance on the wave shapes may be. The analysis has been carried out to a frequency equal to eight times the input alternating frequency. It will be observed that the input current wave shape has been slightly improved at the expense of output voltage wave shape and that a seven per cent average output voltage drop has been caused by the introduction of reactance into the calculations.

In a polyphase rectifier some of the current harmonics do not have to flow clear back to the supply source, but may be short circuited in the transformer with a resulting improvement in regulation and wave shape. Thus if three single-phase rectifiers having waves described in Table V were connected to the three phases of a distribution system, the third-harmonic currents required by the rectifier would circulate between the three transformer primary windings, which might offer considerably less impedance than the supply lines.

An interesting analogy may be drawn between the rectifier and the direct-current generator. In the generator there is a commutating voltage which induces currents to flow in the coil short circuited by a brush. It is customary to increase the commutating voltage with increasing load current, but if the leading edge of the brush could remain fixed while the trailing edge shifted with the rotation in proportion to the load, an equally good load compensation would be secured.

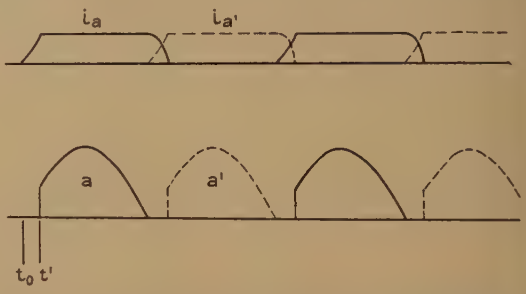

Fig. 11. Output Current and Voltage Waves, Showing Effect of 26 Deg. Period of Short Circuit During which Currents Are Transferred and No Voltage is Produced by the Rectifier

In the rectifier that is exactly what is done. The transfer period is automatically extended until the transfer is complete, just as if the generator brush were widened to compensate for increasing load. The rectifier has the advantage that compensation cannot be over done. The unidirectional conductivity precludes a current reversal which would result in sparking in the generator.

Conclusion

Rectifier current and voltage relations and wave shapes can be readily obtained by neglecting the effects of inductance. The results so obtained are accurate to within a few per cent. Inductance introduces a problem essentially the same as the commutating problem in a direct-current generator, except that the commutating period is lengthened with increase of load instead of the commutating field strength being increased.

TABLE V

RECTIFIER WAVE ANALYSIS

Harmonic	Average	Fundamental	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth
Without Inductance									
Output voltage . . .	0.637	0.0	0.424	0.0	0.0848	0.0	0.0364	0.0	0.0202
Input current	0.0	1.274	0.0	0.424	0.0	0.254	0.0	0.182	0.0
With Inductance									
Output voltage . . .	0.593	0.0	0.49	0.0	0.123	0.0	0.055	0.0	0.032
Input current. . . .	0.0	1.27	0.0	0.39	0.0	0.183	0.0	0.117	0.0

APPENDIX

Derivation of Equation (*1*)

Average voltage E for unity maximum of sine waves for period as shown in Fig. 12.

$$E = \frac{p}{2\pi} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} \cos \theta \, d\theta$$

$$= \frac{p}{2\pi} \Big[\sin \theta \Big]_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} = \frac{p}{\pi} \sin \frac{\pi}{p}$$

Derivation of Equation (*2*)

Referring to Fig. 12.

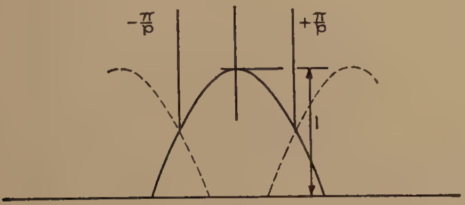

Fig. 12

$$a_n = 2 \frac{p}{2\pi} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} \cos \theta \cos n\theta \, d\theta$$

$$= \frac{p}{\pi} \left[\frac{\sin (n-1)\theta}{2\,(n-1)} + \frac{\sin (n+1)\theta}{2\,(n+1)} \right]_{-\frac{\pi}{p}}^{+\frac{\pi}{p}}$$

$$= \frac{p}{\pi} \left[\frac{\sin (n-1)\frac{\pi}{p}}{n-1} + \frac{\sin (n+1)\frac{\pi}{p}}{n+1} \right]$$

$$= \frac{p}{\pi(n^2-1)} \left[2\,n \sin \frac{n\pi}{p} \cos \frac{\pi}{p} - 2 \cos \frac{n\pi}{p} \sin \frac{\pi}{p} \right]$$

But there can be no values for n less than p because the curve repeats p times per cycle.

Also there can be no values of n which are fractional multiples of p. Therefore $n = mp$ where m is an integer.

$$n \sin \frac{n\pi}{p} \cos \frac{\pi}{p} = mp \sin m\pi \cos \frac{\pi}{p}$$

but $\sin m\pi = 0$ and therefore the first term disappears.

$$- \cos \frac{n\pi}{p} \sin \frac{\pi}{p} = - \cos m\pi \sin \frac{\pi}{p} = \pm \sin \frac{\pi}{p}$$

so that

$$a_n = \frac{\pm 2p}{\pi\,(n^2-1)} \sin \frac{\pi}{p} = \frac{\pm 2E}{(n^2-1)}$$

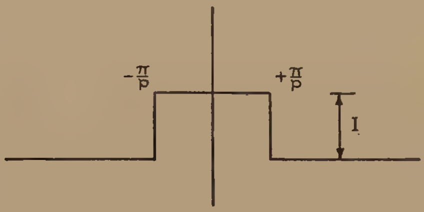

Fig. 13

which is plus for odd values of m and minus for even values.

Derivation for Equation (3)

Referring to Fig. 13.

$$a_n = \frac{I}{\pi} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} \cos n\theta \, d\theta$$

$$= \frac{I}{n\pi} \Big[\sin n\theta \Big]_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} = \frac{2I}{n\pi} \sin \frac{n\pi}{p}$$

Studies of Electric Discharges in Gases at Low Pressures

PART III

TYPICAL EXPERIMENTAL DATA ILLUSTRATING THE USE OF CYLINDRICAL COLLECTORS

By DR. IRVING LANGMUIR and HAROLD MOTT-SMITH, JR.
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Parts I and II of this series of articles appeared in our July and August issues, and dealt with the theory of plane, cylindrical, and spherical collectors (with retarding and accelerating fields) and with typical experimental data on the use of plane collectors together with a discussion of the visual observation of sheaths. The present installment furnishes similar data for cylindrical collectors. The theories, equations, graphs, and tabulations derived in the investigation which is recorded in this series of articles are a very valuable addition to our knowledge, particularly as they apply to electric discharges under conditions that are much more difficult to investigate than were those in vacuum.—EDITOR.

Review of the Characteristics of Cylindrical Collectors

We have seen that when a cylindrical electrode is so charged that it collects only ions of one sign and the mean free path of an ion is large compared to the radius of the sheath, the volt-ampere characteristic will obey one of two different laws, depending upon the relative values of the radius of the collector r, the sheath radius a, the drop of potential in the sheath V, and the temperature T corresponding to the Maxwellian distribution of velocities among the ions. We shall make use of the variable before defined:

$$\eta=\frac{eV}{kT} \tag{56}$$

where e is the charge on the electron, and k is the Boltzmann constant. Then when η is large compared to a/r (Case I), the current i taken by the collector will be limited by the size of the sheath and will be determined by the equation:

$$i=\frac{a}{r}AI \tag{57}$$

in which I is the current density of ions of the sign collected in the ionized gas outside the sheath, and A is the surface area of the collector. In this case the volt-ampere characteristic will follow the space-charge formula:

$$i=\frac{14.68\times10^{-6}}{\sqrt{m/m_e}}\,\frac{lV^{3/2}}{r\beta^2}\left(1+\sqrt{\frac{T}{1640\,V}}\right) \tag{58}$$

where m is the mass of the ion, m_e the mass of an electron, l the length of the cylinder, and β is a function of a/r.

On the other hand, when η is small compared with a/r (Case II), the orbital motion limits the current which is given by the equation:

$$i=AIf_\infty\,. \tag{59}$$

Here f_∞ stands for the limiting value reached by the function f of equation (25) in Part I when a/r becomes large. For $\eta>2$, f_∞ is given with great accuracy by the formula:

$$f=\frac{2}{\sqrt{\pi}}\sqrt{\eta+1}\,. \tag{60}$$

By combining equations (56), (59) and (60), it is seen that in this case a straight line should be obtained when the square of the current is plotted against the voltage. The intercept of this line on the V-axis is

$$V_0=-\frac{kT}{e} \tag{61}$$

while from the slope S can be found the number of ions per cubic centimeter n, from the equation:

$$\begin{aligned} n&=4.03\times10^{13}\sqrt{\frac{m}{m_e}}\,\frac{I}{\sqrt{T}}\,.\\ &=3.32\times10^{11}\frac{\sqrt{S}}{A}\sqrt{\frac{m}{m_e}}\,. \end{aligned} \tag{62}$$

Near the space-potential the square of the current will no longer follow the straight line law, because the function f_∞ is not accurately represented by equation (60) in this region. The exact value of f_∞ for η positive can, however, be calculated from equation (25) of Part I. For negative values of η, f is independent of a/r, and according to equation (1) is given by

$$f = \epsilon^{\eta}, \ \eta < 0. \tag{63}$$

Fig. 7 shows a plot of the square of f_∞ against η calculated in this way. This should be the actual form of the curve obtained by plotting the square of the current against the voltage for a cylindrical collector when the current is determined by the orbital motion of the ions.

Let us put

$$q = \frac{1}{f_\infty} \frac{2}{\sqrt{\pi}} \sqrt{1+\eta}. \tag{64}$$

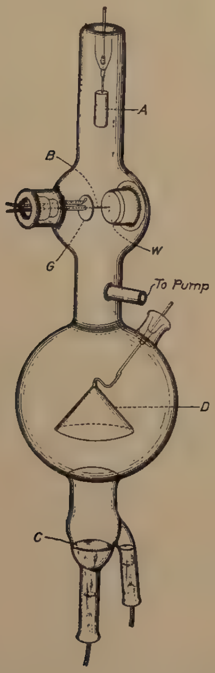


Fig. 6. Mercury Vapor Tube for Observing Sheath Diameters and Thicknesses (*Repeated from Part II*)

Then q will be a function of η which will rapidly approach unity as η becomes positively infinite. The values of q^2 are given in Table IX. If experimentally measured values of the square of the current are multiplied by the appropriate values of q^2, points are determined which should lie in a straight line even near the space potential.

With given values of the current density I and temperature T of the ions, we can obtain volt-ampere characteristics following either Case I or Case II by a suitable choice of the collector radius. If the collector is sufficiently large, the sheath formed about it will only slowly increase in size as the potential is raised, a/r will be small compared to η, and the space charge equation will hold. For a sufficiently small collector large values of a/r will be reached at low voltages and the current will be limited by the orbital motion along the whole characteristic. Now from the current collected by a large cylinder and the observed size of the sheath around it, we can determine I from equation (57), while the characteristics of a small collector will enable us to find n by using equation (62). Thus, if we have two cylindrical collectors of suitable radii placed near each other in an ionized gas, we can calculate from their characteristics and from

TABLE IX

Values of the function q^2. [See equation (64)]

η	q^2	η	q^2
−1.0	0.000	0.8	1.064
−0.8	1.261	1.0	1.0518
−0.6	1.691	1.4	1.0360
−0.4	1.700	1.8	1.0265
−0.2	1.520	2.2	1.0207
0.0	1.273	2.6	1.0167
0.2	1.159	3.0	1.0138
0.4	1.108	4.0	1.00970
0.6	1.082	5.0	1.00724

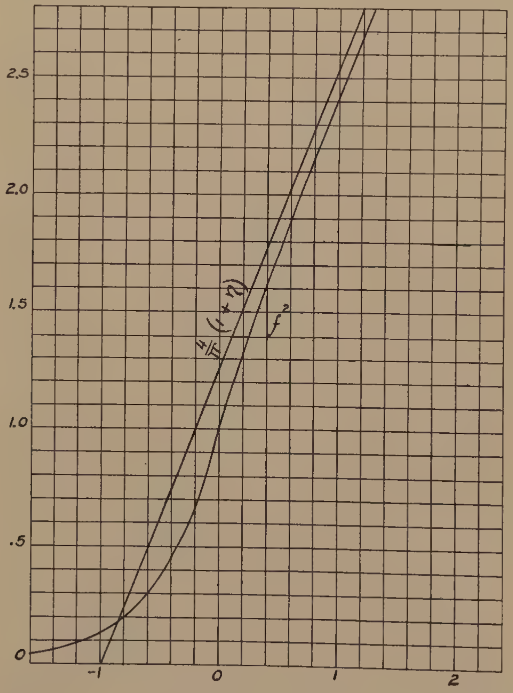


Fig. 7. Plot of Square of *f*-function and Approximation Formula [See equation (60)]

the observed radii of the sheaths the values of the quantities *n*, *I*, and *T*, provided only that the ionized gas is sufficiently homogeneous that these quantities are the same in the region about each collector.

As with plane collectors, the volt-ampere characteristic of a cylindrical collector consists of three parts: (1) a range of potential where positive ions only are being received; (2) a transition region where the electrode collects both positive ions and electrons moving against a retarding field; (3) a part where the potential is accelerating the electrons and the positive ion current received is negligible compared to the electron current. The parts (1) and (3) will follow the laws just discussed, while from part (2), after correcting for the positive ion current, the law of distribution of velocities among the electrons (or negative ions) can be found. We have seen that if this law is the Maxwellian one, a straight line should be obtained when the logarithm of the current is plotted against the voltage, regardless of the shape of the collector. The experimental data show that with a cylindrical collector as well as with a plane one such a straight line is actually obtained, under normal conditions. The deviations from a straight line are usually much less for the cylinder than for the plane, especially when a small wire is used as a collector. This is probably due to the fact that the wire draws much less current than the plane, and so does not disturb appreciably the equilibrium conditions in the ionized gas.

Typical Experimental Data for Cylindrical Collectors

As an example of the logarithmic plot obtained with a cylindrical collector under normal conditions, we may take Fig. 8. The data for this plot were obtained by using electrode B of the mercury arc tube illustrated in Fig. 6, the dimensions of the collector being: length ¾ in., diameter 7 mils. The current to the main anode at the time the data were taken was 0.15 amp., and the water bath temperature was 12 deg. C., corresponding to a mercury vapor pressure of 0.73 bar. It is seen that a very good straight line is obtained over a range corresponding to a hundred-fold increase of the current. The lower points were located by subtracting from the total current the positive ion current extrapolated from the i^2-E plot for positive ions; this amounted to a considerable correction for the lowest points (about 50 per cent of the total current at −20 volts), yet these points fall closely on the straight line determined by the upper points. The change of slope above the space potential is very gradual because of the rapid growth of the electron sheath, but by plotting the square of the current against the voltage a straight line can be found by means of which the space potential is located quite closely. The value found is indicated at the upper end of the curve, and is −3.3 volts.

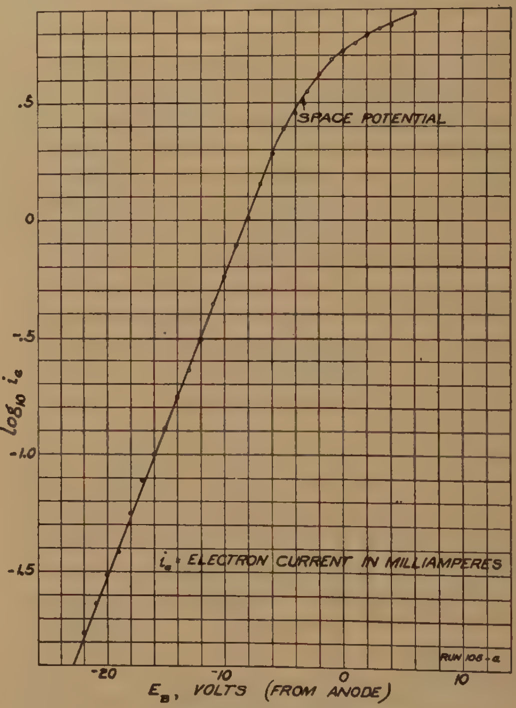


Fig. 8. Semi-logarithmic Plot of Current-voltage Curve for Collector B

In order to study the behavior of two cylindrical electrodes of different radii in the same arc, a tube was constructed similar to that of Fig. 6, but having two straight wires placed one above the other, perpendicular to the axis of the tube, and arranged so that the sheaths formed could be observed through a plain polished glass window. The dimensions of these electrodes were:

Collector F:
radius 0.00635 cm., length 1.91 cm.
(surface area 0.0762 cm.^{2})

Collector G:
radius 0.156 cm., length 1.91 cm.
(surface area 1.87 cm.^{2})

The ratio of the radii was therefore 25 to 1, and it was found possible to adjust the arc current so that the current to the larger collector was limited by space charge, while the current to the smaller was determined by the orbital motion when positive ions were being collected.

The collecting wires were sealed into a bulb five inches in diameter, which was joined to the cathode chamber below and the anode chamber above by short connecting tubes 1¼ in. in diameter. When the pressure of mercury vapor was of the order of one bar, the glow in the bulb was quite uniform, but the relatively narrow constriction at the lower end caused a beam of high-velocity electrons to issue from the connecting tube. This beam distorted the positive ion sheaths formed when negative voltages were applied to the collectors. Instead of being circular, the sheaths were narrower on the side exposed to the beam than on the other or upper side. Beyond the upper edge of the sheath was a slightly darkened region bounded by a hyperbolic curve, and it was apparent that this was the "shadow" cast by the sheath in the beam of high-velocity electrons.

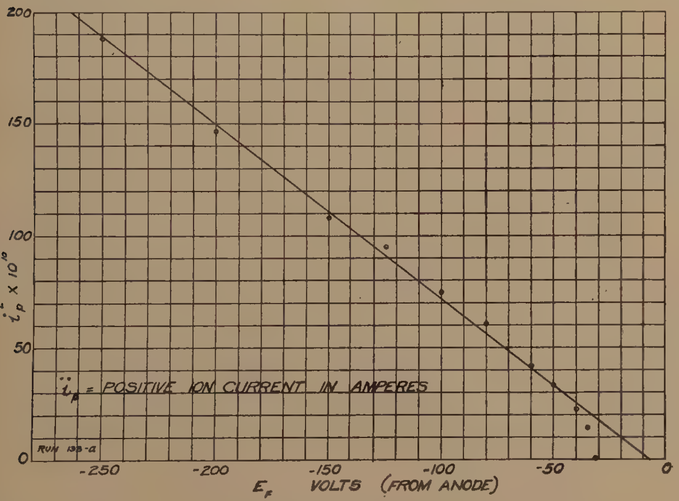


Fig. 9. Plot of Square of Positive Ion Current Against Voltage for Collector F

Under these circumstances we should no longer expect that the distribution of velocities of the electrons entering the sheath would be Maxwellian, and as a matter of fact it was found that the logarithmic plot of the electron current showed marked deviations from a straight line. It was possible, furthermore, to interpret these experimentally determined curves as being due to a Maxwellian distribution upon which was superimposed another distribution, non-Maxwellian but centering about a mean velocity higher than that of the Maxwellian one. At a pressure of one bar the mean free path of an electron was comparable with the dimensions of the bulb, so that the high-velocity electrons starting from the lower part of the bulb were able to reach the sheath without losing energy by collisions. At higher pressures, however, the beam should be destroyed through collisions with heated atoms, and the distribution of electrons in the center of the bulb should be of the normal or Maxwellian type. This was found to be the case, for at a temperature of 60 deg. C. when the mean free path was only a tenth of the bulb radius, the logarithmic plot became straight and the sheaths were circular.

By means of a magnet it was found possible to deflect the beam away from the sheaths, so that approximately normal curves could be obtained. This magnet was used throughout in working at temperatures less than 40 deg. C. A typical set of data obtained in this way is illustrated by the curves in Figs. 9, 10, 11 and 12, and in Table X. The arc current was one ampere and the temperature of the water bath 14.1 deg. C., so the vapor pressure of the mercury was 0.91 bar. The voltages of F and G were all measured with respect to the anode A.

Fig. 9 is a plot of the results obtained by using F to collect positive ions. The sheath diameters were not measured in this run as their values do not enter into the calculations; but observations made in previous experiments had shown that under the conditions of the present run the characteristic of F should fall in Case II, the current being entirely determined by the orbital motion. In accordance with this conclusion we see that the square of the current when plotted against the voltage gives a line nearly straight. From calculations to follow it will appear that the space potential is -9.4 volts measured with respect to the anode A, and that the velocities of the electrons correspond to a temperature of 42,500 deg. If we estimate the velocities of the positive ions to be roughly one-half of this, we arrive at a value of about 2 volts for the V_0 of equation

(61), which means that the straight line should pass through the point −7.4 on the V-axis in Fig. 9. The line shown was drawn so as to have this intercept and fit as closely as possible the experimentally determined points. The slope of the line is 0.771×10^{-10} amp.²/volt, and by equation (62) this gives directly for the number n_p of positive ions per cm.³ in the ionized gas near the collector:

$$n_p = 23.2 \times 10^9 \text{ amp.}^2/\text{volt.} \qquad (65)$$

The deviation of the points at the lower end of the graph from the straight line is caused by the arrival of electrons, which begin to be collected in appreciable numbers at potentials higher than −40 volts. Using the straight line of Fig. 9 to calculate the extrapolated values of the positive ion currents, the electron current to F was computed and plotted on semi-logarithmic paper. The result showed the ionized gas about the sheath was still disturbed from the normal condition, for the points did not lie upon a single straight line. It was possible to represent them as lying upon three straight lines; one extending from the space potential over a range of 84 per cent of the total current with a slope of 3.41 volt⁻¹; a second covering 14 per cent of the current with a slope of 5.14 volt⁻¹; and a third corresponding to the remainder of the current, 2 per cent with a slope of 3.13 volt⁻¹. When the current to a collector is determined by the orbital motion, each class of electrons having a given velocity will contribute its quota to the current collected independently of the presence of electrons of other velocities. The currents due to two different classes will simply add. Hence in the present case, since 84 per cent of the electron current has a Maxwellian distribution corresponding to a value of 3.41 for V_0, we should expect that the current taken by F with voltages accelerating the electrons should be nearly the same as if all the electrons had the velocities proper to this Maxwellian distribution. To obtain a better approximation which cannot be seriously in error, it seems logical to take the weighted mean of the three slopes. If this is done the value 3.66 is obtained for V_0. We are justified in assuming that the electron current taken by F will be limited by the orbital motion because the positive ion current was so limited, and the characteristics of an electrode depend essentially upon the values of n and of T, which cannot be very different for positive ions and for electrons in the same mass of ionized gas.

Continuing the volt-ampere characteristic beyond the space-potential point or kink in the logarithmic plot, we once more obtain a line nearly straight when the square of the current is plotted against the voltage, as in Fig. 10. Taking the value of V_0 to be 3.66 volts and using the q-function to correct the position of the lower points we obtain the straight line shown, the crosses marking the points obtained by the use of the q-function. The intercept of this line is −13.06 volts, and the space potential is consequently determined to be

$$-13.06 + 3.66 = -9.4 \text{ volts} \qquad (66)$$

measured from the anode. This gives by far the most certain method of finding the space potential. The kink in the logarithmic plot of the electron current gives a value which is usually subject to an uncertainty of a volt or two even with large plane electrodes; but the value of the intercept of the straight line in Fig. 10 can easily be estimated to within a few tenths of a volt.

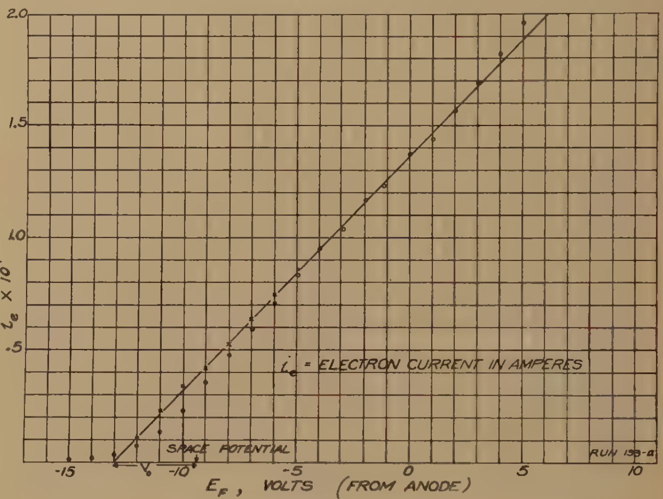


Fig. 10. Graph Illustrating Use of i^2-E Plot to Obtain Space Potential of Collector F

When the potential of the collector is more than ten volts above that of the space, the electrons falling through the sheath will be accelerated sufficiently to ionize the gas molecules, and as a result the equations developed will no longer hold. This causes the deviation from the straight line of the upper points in Fig. 10. Therefore only the points lying between the limits of about 4 to 12 volts positive with respect to the space are available for the location of the straight line, unless use is made of the q-function, in which case the best straight line will be determined by a series of approximations since the value of the argument η of the q-function depends upon the value assumed for the space potential.

The slope of the straight line in Fig. 10 is 10.4×10^{-6} amp.^{2}/volt, which gives by equation (62) for the number of electrons per cm.^{3} in the ionized gas about F:

$$n_e = 14.0 \times 10^9/\text{cm.}^3 \tag{67}$$

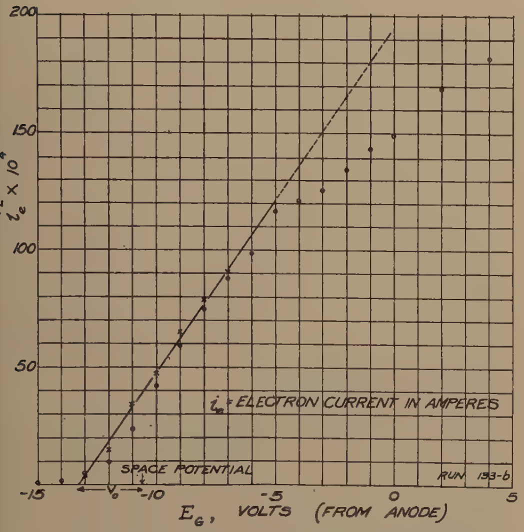


Fig. 11. Plot of Square of Electron Current Against Voltage for Collector G. (Crosses mark points obtained by use of q-function)

From equation (62) we can also find $I_e/\sqrt{T_e}$. Taking the value $T_e = 42{,}500$ deg. found above from the slope of the logarithmic plot, we thus find for the electron current density

$$I_e = 71.6 \times 10^{-3} \text{ amp./cm.}^2 \tag{68}$$

It might be thought that an independent way of finding I_e would be to read off directly from the volt-ampere characteristic the current taken by the collector when it was at the space potential and divide this by the area of the collector. This is not an independent method, however, because the value of the space potential itself was calculated from the i^2-E plot. But the fact that the value so found for the space potential falls within the limits that are estimated from the kink in the logarithmic plot, as well as the fact that the plot of the square of the electron current against the voltage gives a curve of the theoretical type illustrated in Fig. 7, justifies our assumption that the electron current to F is limited by the orbital motion. It is to be noted that the fact that the points in Fig. 10 fall close to a straight line does not prove that assumption, for a good straight line can be obtained even when the current is limited entirely by space charge, as well as in cases intermediate between the two extremes. In general, however, these lines will give values for the space potential and for n that are clearly in error.

Turning now to the observations made with the large collector G, let us first consider the electron current characteristic. In the range from -408 to -10 volts G collected an electron current which, when corrected for the positive ion current and plotted on semi-logarithmic paper, gave a line approximately straight with a slope corresponding to $V_0 = 2.70$ volts. The kink in this line showed that the space potential was -10.5 ± 0.5 volts. Beyond this point the current increased more slowly, and on plotting the square of the current against the voltage the points shown in Fig. 11 were obtained. In the range from -13 to -5 volts the points fit fairly well with values calculated from equation (59), assuming the space potential to be -10.6 volts. This is shown by the fact that the points marked by crosses, which were obtained from the observed currents by the use of the q-function, lie fairly close to a straight line. The slope of this line is 14.7×10^{-4} amp.^{2}/volt, which by equation (62) corresponds to an electron density:

$$n_e = 6.80 \times 10^9/\text{cm.}^3 \tag{69}$$

Using the value of V_0 found above, the electron current density is found to be

$$I_e = 29.8 \times 10^{-3} \text{ amp./cm.}^2 \tag{70}$$

In using equation (59) we have tacitly assumed that the characteristic of G falls under Case II. The value of the space potential found under this assumption agrees well with that estimated from the logarithmic plot, and the value of n_e calculated from the slope is of the right order of magnitude. This points to the rather remarkable conclusion that even with a collector as large as G the current is limited entirely by the orbital motion for sufficiently low accelerating voltages, while at higher voltages the current is limited entirely by space charge as is indicated in Fig. 11 by the falling off of the current beyond $E_G = -5$ from the value corresponding to the dotted line. Experiments made under different conditions show that the result holds up to quite high values of the arc current and at high mercury vapor pressures, even though under these conditions the ion velocities are small. The explanation is probably as follows. For each value of the accelerating voltage there is a certain minimum value which the sheath radius must exceed in order that the current be effectively limited by the orbital motion, the minimum value increasing with the voltage. At low voltages the actual sheath radius exceeds this critical value even with a large collector, but as the voltage is raised the sheath radius eventually falls below the critical value, since the sheath increases only slowly in size around a collector of large radius. At first, therefore, the current will be limited by the orbital motion, then there will be a transition region, and finally the current will be limited by space charge. However, the conclusion cannot be regarded as completely proved since it is not known how much the slope and intercept of the straight line will deviate from the values given by equations (61) and (62) when some case intermediate between the two extremes holds. Pending a more detailed theoretical analysis of this problem, the conclusion can at least be regarded as a convenient working hypothesis, since it leads to reasonable values for the space potential and for n_e under a wide range of variation of the experimental conditions.

The results of using G to collect positive ions are shown in Table X and Fig. 12. Column 1 of the table gives the potential applied to G, measured from the anode; column 2 is the potential with respect to the space. The observed positive ion currents are given in column 3, while in column 4 are the values of the sheath radius which in this case were measured directly with the cathetometer. Dividing these by the radius r of the collector gives the ratios shown in column 5. Using these observed values of a/r and the corresponding values of V, it is found from a consideration of the f-function that with any reasonable assumption as to the velocities of the positive ions the current should be wholly limited by space charge. Consequently the current should be proportional to the sheath radius, and the constancy of the values of $i\ (r/a)$ given in column 6 show that this is so. The average value of $i\ (r/a)$ is 0.266 m.a., and on dividing this by the area of the collector the positive ion current density is found to be

$$I_p = 1.42 \times 10^{-4} \text{ amp./cm.}^2 \qquad (71)$$

On comparing the data obtained with F and G there are seen to be wide divergences in the values of n_e, I_e, and T_e for the two collectors. This makes it impossible to correlate the values of I_p obtained from G and of n_p obtained from F to calculate T_p, the temperature of the positive ions. These divergences were undoubtedly due to faults in the construction of the tube, which are now being corrected. The data just given serve however to illustrate the method, which should certainly succeed in a tube of proper design. Ordinarily the calculated value of T_p would be used together with the observed values of the sheath radius about G to compute the current to G by the space charge equation (58) as a check upon the observed values. In the present case it is found that if T_p is assumed to be 3500 deg. the values of the current given in column 7 of Table X are obtained, which are in good agreement with the observed values in column 3, except for the bracketed numbers which are probably affected by experimental error in determining a. This value of T_p is undoubtedly much too low, however, and no weight can be put upon this method for its estimation, since the values of T_p found by it are greatly affected by errors in measuring the sheath radius.

TABLE X

Positive Ion Current to Cylindrical Collector G (radius 0.156 cm., length 1.91 cm.) Run 133-b. Arc Current = 1 amp. Mercury Vapor Pressure = 0.91 bar.

1	2	3	4	5	6	7
E_G Volts	V Volts	i m.a.	$a_{obs.}$ cm.	a/r	$i\frac{r}{a}$ m.a.	$i_{calc.}$ m.a.
−400	−389.4	0.795	0.472	3.02	0.263	0.812
−350	−339.4	0.750	0.451	2.89	0.260	0.749
−300	−289.4	0.705	0.422	2.70	0.261	0.715
−250	−239.4	0.662	0.393	2.52	0.263	0.662
−200	−189.4	0.615	0.362	2.32	0.265	0.612
−150	−139.4	0.545	0.305	1.95	(0.279)	(0.717)
−125	−114.4	0.518	0.295	1.89	(0.274)	(0.606)
−100	−89.4	0.487	0.285	1.83	0.266	0.488
					Ave. 0.266	

In Fig. 12 is shown the plot of the square of the positive ion currents to G against the voltage. It is seen that a straight line can be drawn so as to fit the observed points fairly closely, even though the current in this case is entirely limited by space charge. This illustrates the remark previously made, that the straightness of the i^2-E plot cannot be used as a criterion to find whether the current *is limited by* the orbital motion. It is obvious, however, that the straight line in Fig. 12 cannot be made to fit equation (59), for the intercept on the V-axis is 77 volts measured from the space potential, a quantity certainly much greater than eT_p/k. The meaning of this intercept and of the slope could be found by eliminating the sheath radius a from equations (57) and (58) to obtain the relation between the current and the voltage. This is difficult to do on account of the complicated form of the space charge equation unless the effect of the initial velocities is neglected. The resulting formula can be expected to hold when the potential applied to the collector is large compared with the initial velocities.

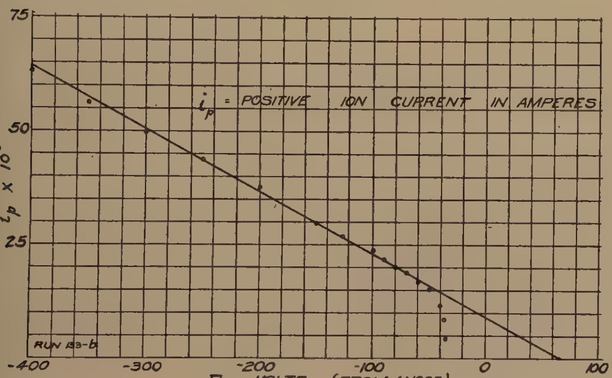


Fig. 12. Plot of Square of Positive Ion Current Against Voltage for Collector G

Table XI summarizes some of the data obtained with collectors F and G. Column 1 gives the temperature of the water bath; column 2, the corresponding pressure of the mercury vapor; column 3, the current to the anode A maintained during the run. Column 4 specifies the collector used. In column 5 are the values of the space potential, referred to the anode A, obtained as in Figs. 10 and 11. In every case the values of these space potentials fall within the nearest limits that can be estimated from the kink in the logarithmic plot of the electron current. Column 6 gives the temperature of the electrons, as determined from the slope of the logarithmic plot. Column 7 contains the value of the electron density determined as in Figs. 10 and 11 from the slope of the i^2-E plot. Using values of n_e and of T_e from column 6, the electron current density given in column 8 was calculated. Column 9 gives n_p found from the positive ion characteristic of F, and column 10 the positive ion current density near G found by using the observed sheath diameters.

TABLE XI

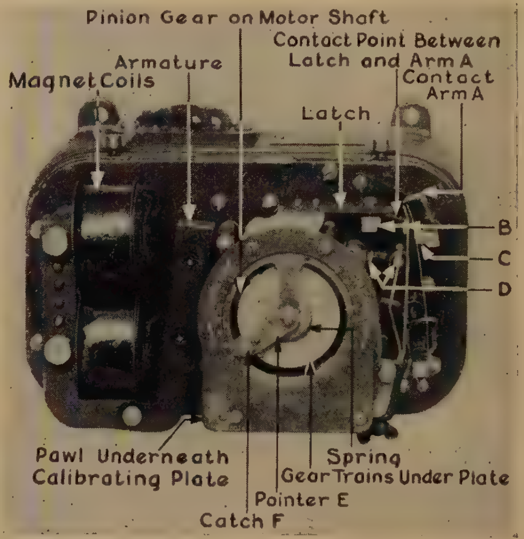
Summary of Data Taken with Collectors F and G

Run No.	1 Bulb Temp. Deg. C.	2 Vapor Pressure, Bars	3 i_A Amp.	4 Collector Used	5 Space Potential Volts	6 T_e Deg. K	7 n_e ×10⁻⁹	8 I_e m.a./cm.²	9 n_p ×10⁻⁹	10 I_p m.a./cm.²
128	13.0	0.81	0.080	F	−9.5	28,800	0.112	4.76	0.118	
				G	−8.1	39,200	0.532	2.61		0.0108
130	13.0	0.81	0.30	F	−7.0	50,400	4.73	27.4	7.96	
				G	−9.6	41,300	2.12	9.29		0.0445
133	14.1	0.91	1.0	F	−9.4	42,500	14.0	71.6	23.2	
				G	−10.6	31,300	6.80	29.8		0.143
134	40.1	8.0	0.30	F	−9.3	19,900	1.87	6.54	4.93	
				G	−9.0	18,100	1.23	4.14		0.0170
135	40.1	8.0	1.0	F	−9.1	16,900	7.20	23.2	17.3	
				G	−9.6	14,300	4.71	13.9		0.0603
136	0	0.23	0.30	F	−6.4	29,900	6.30	24.3	11.7	
				G	−6.5	26,600	4.29	17.3		0.0603
137	0	0.23	1.0	F	−7.9	31,500	18.3	79.5	30.3	
				G	−9.1	32,100	9.75	43.4		0.196

(*To be continued*)

Alternating-current Definite-time Relay for Use with Magnetic Controllers

The need for an alternating-current definite-time relay of sturdy construction and increased accuracy has led to the development of a new model. This device is especially applicable to automatic starters for alternating-current motors where a definite-time interval is necessary between the closing of contactors in accelerating the machine. In its field of application lie automatic compensators and the control of motor-driven sugar extractors, dough mixers, dyeing machines, pumps operating against a high head, etc. As an illustration of a particular adaptation, the contacts of the relay may be so arranged that when it is used with the starter of a synchronous motor it will also energize the field circuit after sufficient time has elapsed for the motor to come up to speed.


Pinion Gear on Motor Shaft
Contact Point Between Latch and Arm A
Armature
Magnet Coils
Contact Arm A
Latch
B
C
D
Pawl Underneath Calibrating Plate
Spring
Gear Trains Under Plate
Pointer E
Catch F

The relay is constructed of the following parts:

(a) A small bipolar constant-speed induction motor

(b) Two magnet coils that pick up the armature which operates the contacts through a link mechanism

(c) A gear train carrying a disc to which is fastened a stud that trips a latch

(d) A timing mechanism with a calibrated scale and pointer

As shown in the illustration, the contacts, timing device, and magnet coils are mounted on the front of a metal plate, and are normally enclosed in a dust-tight sheet-metal cover. The motor, attached to the back of the metal plate, is enclosed in a cast-iron case.

When the start button is pressed the motor and magnet coils are energized through the normally closed contact C. This causes the motor to rotate and the relay armature to pick up, making contact at D, which short circuits the start button and completes the holding circuit. At the same time a pawl meshes with the gear train which starts to rotate in a counter-clockwise direction carrying with it the tripping mechanism. The contact has not yet been made at B nor broken at C because of the latch holding up the flexible contact arm B.

As the gear train rotates it requires a definite time, depending upon the setting of the relay, for the stud to reach the latch and trip it. Tripping the latch releases the contact arm A, contact being made at B and broken at C. Breaking the contact at C disconnects the relay motor. The final action which follows the making of contact at B depends upon whether the relay is used with an automatic compensator or other type of starter.

When the relay is de-energized, the pawl is disengaged and the spring on the support for the gears returns them to the normal position. The relay armature with the contacts also returns to the starting position.

The time delay is determined by the arc through which the tripping mechanism must be turned by the motor before it actuates the contacts. By means of the pointer and calibrated scale, various time settings may be obtained.

The contacts of the relay will have a current-carrying capacity ample for the control circuit of any automatic magnetic starter.

Studies in the Projection of Light

PART XII

DESIGN OF THE GLASS PARABOLOIDAL MIRROR

By Frank Benford

Physicist, Illuminating Engineering Laboratory, General Electric Company

In this part of the series of articles on light projection the author takes up the design of the so-called paraboloidal mirror, and after a preliminary word in explanation for the use of glass instead of metal in even the most rigorous types of service, he points out that the use of glass leads to a new form of surface for the second or silvered face of the mirror. This surface is not parabolic in section, but has a form derived from the optical relation between it and the front paraboloid, and hence is called a co-paraboloid. Three independent beams originating at the two mirror faces singly and in combination are traced out, and the conditions for optical coincidence between the three are laid down. Two mathematical methods for computing the co-paraboloid are developed, and it is shown that the shorter of the two methods gives data of high accuracy with a great saving of work. The general features of the glass mirror, such as the thickness of glass and its refractive index, are discussed in relation to the short method of computation.—Editor.

The Necessity for Glass Mirrors

One of the most desirable features of almost any commercial article is durability. The telescope of the astronomer may have a silver surface exposed to the air, which exposure results in slow oxidation of the silver, but the astronomer is highly skilled in the art of combating oxidation without altering the optical properties of the mirror and he can keep the surface in good condition. The same degree of skill cannot reasonably be expected of the attendant of a searchlight, particularly if the light is in military service. In times of peace the searchlight may receive the best of attention, but the real test comes in the stress of war, when untrained men must care for strange equipment under conditions that often would not permit them to work with skill at the trade they know best. It may be somewhat of a mental shock to think of a glass mirror as being more durable and dependable than a metal mirror, but such is indeed the case.

It is one of the commonest opinions held by the uninformed that only the general outline of a mirror is of importance, and that given a paraboloidal form the surface may be covered with minute scratches without optical damage. This idea, carried into practice, sometimes has the effect of causing the disappearance of 20 or 30 per cent of the light, and the material of the reflector is then thought to be inferior. Any scratch absolutely wipes out the optical efficiency of the area covered, and if a metal mirror is covered with a maze of scratches there will be a large loss of light through scattering. The very best of the reflecting metals, such as silver or gold, are soft, and any ordinary cleaning process soon ruins them. By adding a protecting cover of glass, the metal is protected from oxidation or mechanical injury and the optics, from a designing and manufacturing standpoint, reduces to the problem of grinding and polishing the glass. The metal reflector, say silver, is applied to the finished surface of the glass and takes its form, so we may drop the metal from further consideration and concentrate our attention on the glass itself.

In recent years an extremely durable form of glass mirror has been developed. This is the wire-backed mirror, which has a fine wire screen fitted to the back and held principally by the coating of protective paint. It has been demonstrated that a number of rifle bullets may be fired through such a mirror without more than local damage for each bullet, and even if the mirror is broken entirely across in a number of places the wire screen holds the pieces in optical alignment even when subjected to heavy shocks. It is doubtful if any metal mirror of equal weight could come through such a test with equal optical effectiveness at the end.

The First Surface

For convenience of discussion, we may consider the searchlight beam to be composed of three independent parts. First, a beam of some 5 per cent strength of light reflected from the first surface; second, a beam of about 90 per cent strength reflected once at the second surface; and third, a beam of less than 5 per cent strength composed of light reflected internally between the two surfaces.

The light reflected from the first surface is computed by Fresnel's familiar formula

$$I_1=\frac{I_0}{2}\left[\frac{\sin\,(a-g)}{\sin\,(a+g)}\right]^2+\frac{I_0}{2}\left[\frac{\tan\,(a-g)}{\tan\,(a+g)}\right]^2 \qquad (120)$$

where

a is the angle of incidence upon the glass
g is the angle of refraction within the glass
I_0 is the intensity of the incident light, and
I_1 is the intensity of the reflected light.

At normal incidence, formula (120) reduces to

$$I_1=I_0\left(\frac{n-1}{n+1}\right)^2 \qquad (121)$$

where n is the refractive index of the glass, here taken as 1.52, and leading to an intensity of reflected light of 0.0425 I_0 for reflection from a single surface.

At 30-deg. angle of incidence, which is about the extreme value for the standard form of 60-deg. mirror, we get by equation (120)

$$I_1=0.0444\ I_0$$

It is evident that the reflection of light is nearly independent of the angle of incidence for angles of less than 30 deg. and we may assume an average value of

$$I_1=0.044\ I_0$$

as representing the first surface beam from the entire mirror.

The silver backing reflects about 92 per cent of the light incident upon it, but for the usual grade of glass some 3 per cent is lost in a single traverse, or 6 per cent for the entire path into the mirror and out again.

The intensity of the light penetrating the first surface has just been determined by the computation of the initial reflection, and the same percentage of loss occurs upon traversing the same surface upon emerging. Setting down the various factors of transmission through the surface, transmission through the glass, reflection on the silver surface, transmission through the glass again, and transmission through the glass surface again, we get the emergent main beam,

$$I_2=0.956\times0.97\times0.92\times0.97\times0.956\ I_0$$
$$=0.792\ I_0.$$

The computation of the third beam composed of the multiple internal reflection is, when rigorously computed, a matter of some complication; but it is simple enough if we assume, as has just been done, that the reflection is independent of the angle of incidence upon the glass surface or upon the silver surface.

In Fig. 137 a ray FA is incident at the point A, and part of this ray is reflected along AG and part is refracted along AD. Upon reflection at D it strikes the first surface at B and emerges along the line BH. Let us now take the ray FB that strikes the point B and trace its two parts BH, and BE—EC—CI. The path BH is therefore common to light incident at both A and B. The two rays FB and BH make equal angles with the normal BN, and hence the refracted paths BE and DB of these rays within the glass must make equal angles with the normal. From this it follows that the light along BD is split into an external element along BH and an internal element reflected along an identical path BE with the light incident at B. Therefore each internal reflection takes place in such a manner as to conserve it for partial emission in the correct direction at each succeeding contact with the first surface.

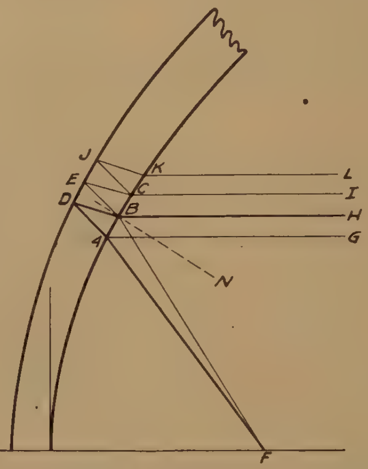


Fig. 137. The ray AG is reflected from the first surface only. The ray BH represents the main beam and is reflected from the second surface. The rays CI and KL represent an infinite series of internally reflected rays that contribute some three per cent to the total beam

Let r = the reflection at the first surface
k = the reflection at the silvered surface
t = the transmission through a single thickness of glass
FA represent the strength of the ray in the path FA upon arriving at A and
AD represent the strength of the ray in the path AD upon arriving at D, etc.

We have, considering only the ray along FA,

$$FA = I_0 \quad (122)$$
$$AG = I_0 \, r \quad (123)$$
$$AD = I_0 \, (1-r) \, t \quad (124)$$
$$DB = I_0 \, (1-r) \, k \, t^2 \quad (125)$$
$$BH = I_0 \, (1-r)^2 \, k \, t^2 \quad (126)$$
$$BE = I_0 \, (1-r) \, k \, r \, t^3 \quad (127)$$
$$EC = I_0 \, (1-r) \, k^2 \, r \, t^4 \quad (128)$$
$$CI = I_0 \, (1-r)^2 \, k^2 \, r \, t^4 \quad (129)$$
$$CJ = I_0 \, (1-r) \, k^2 \, r^2 \, t^5 \quad (130)$$
$$JK = I_0 \, (1-r) \, k^3 \, r^2 \, t^6 \quad (131)$$
$$KL = I_0 \, (1-r)^2 \, k^3 \, r^2 \, t^6, \text{ etc.} \quad (132)$$

The light reflected from the front surface is

$$I_1 = I_0 \, r \quad (133)$$

The light reflected *once* from the silvered surface is, from (126),

$$I_2 = I_0 \, (1-r)^2 \, k \, t^2 \quad (134)$$

The light due to multiple internal reflection is, by (129) and (132),

$$\begin{aligned} I_3 &= CI + KL + \ . \ . \ . \\ &= I_0 \, (1-r)^2 \, k^2 \, r \, t^4 + I_0 \, (1-r)^2 \, k^3 \, r^2 \, t^6 + \ . \ . \ . \\ &= I_0 \, (1-r)^2 \, k^2 \, r \, t^4 \, [1 + k \, r \, t^2 + k^2 \, r^2 \, t^4 + \ . \ . \ . \ ] \\ &= \frac{I_0 \, (1-r)^2 \, k^2 \, r \, t^4}{1 - k \, r \, t^2} \quad (135) \end{aligned}$$

Finally

$$I = I_1 + I_2 + I_3 \quad (136)$$

and substituting numerical values

$$\begin{aligned} I &= 0.044 \, I_0 + 0.792 \, I_0 + 0.031 \, I_0 \\ &= 0.867 \, I_0 \end{aligned}$$

Calling the strength of the combined beam 100 per cent, we find that 91.5 per cent is reflected once from the silvered surface, and 8.5 per cent is either direct first surface reflection or multiple internal reflection. There is a real distinction to be drawn between these two beams. Thus it is possible, as indeed is done in the Mangin mirror, to use the 91.5 per cent and wholly waste the 8.5 per cent. Aside from the waste of light there is a decided objection to the misuse of this 8.5 per cent in mirrors that are approximately parabolic. Any stray light added to the region surrounding the main beam adds to the back glare and materially reduces the effective range. In the Mangin type of mirror this stray light is so far out of coincidence with the main beam that it has but little influence upon the searching power of the beam. We thus have the choice of making the two surfaces of widely varying focal length, or of making them of exactly the same effective focal length. The latter solution leads to the paraboloidal front surface and the co-paraboloidal back surface.

The Co-paraboloid, or Ideal Second Surface

It is one of the remarkable features of the silver backed paraboloidal mirror that the silvered surface, which takes an active part in the reflection of 95 per cent of the light in the beam, is not a paraboloid. Just why this is so will be gone into in detail in the following paragraphs; and for the present, for the sake of clarity and brevity, let us christen this second surface a co-paraboloid, or surface that co-operates with the true paraboloidal front surface. There is some five per cent of the beam light that is reflected directly from the front surface and does not penetrate the glass at all. If this light is to be used in strengthening the beam then the front surface must be a true paraboloid, and the second surface remains to be determined. Granting for the moment that the second surface is not a paraboloid, it will be realized that the particular form taken by it has no optical reason for existence except to adjust it optically to the front surface. It is dependent for both its existence and its action on the presence of a paraboloid and we may thus consider the co-paraboloid to be a member of the paraboloid family by marriage rather than by blood.

Exact Computation of the Co-paraboloid

In many optical problems, such as the design of a condensing lens, it is customary to solve for the condition of equal paths, that is, the optical path from filament to image must be the same for all parts of the lens. By path length is meant the time taken by a light ray to traverse it, just as we often express the distance between two towns as being four hours' travel. We might therefore express the path length in, say billionths of a second, but a more convenient way is to express it in centimeters, taking each centimeter in air at its actual length, and multiplying each centimeter in glass by the refractive index of the glass. When the ray traverses glass, or other optical medium denser than air, the optical path therefore exceeds the linear path by an amount proportional to the thickness of the dense medium and to the excess of its index over that of air.

In the case of the paraboloid the one focal point is the focus of the generating parabolic curve, and the other focal point is at either plus infinity, in the forward direction of the beam, or at minus infinity, in the backward direction of the beam. The obvious difficulties of the equal path method in this case may be avoided by considering the path to some plane perpendicular to the axis of the beam, and solving for equal paths from the source to the mirror and then to the plane.

Consider a light source at the focal point (F, O), Fig. 138, to give off a single pulse of light. The light will expand as a spherical shell about (F, O) as a center, and the direction of propagation will be radial, or normal to the shell at each point. After reflection at the mirror the individual paths of each element of the wave front will be parallel to the axis, and the wave front, which must be perpendicular to these parallel paths, is therefore a plane which is perpendicular to the direction of propagation. Let us consider this wave front when it reaches a distance x_4 from the vertex of the front surface paraboloid, Fig. 138. The ray on the axis has traversed a linear distance

$$D_0 = F + T_0 + T_0 + x_4 \qquad (137)$$

where T_0 is the thickness of the glass on the axis, and F is the focal length of the front paraboloid. If the refractive index of the glass is n (in this case we can take $n = 1.52$), then the optical path length is

$$P_0 = F + 2n\,T_0 + x_4. \qquad (138)$$

Let us take some other ray radiated at an angle a from the axis, and call the coördinates of the point where it intersects the front surface (x_1, y_1), then the path length to (x_1, y_1) is $F + x_1$, taking the vertex as the origin of ordinates. Let the point of reflection at the back surface be (x_3, y_3), and the point of emission at the front surface be (x_2, y_2). Let L_1 be the linear length of path between (x_1, y_1) and (x_3, y_3) and let L_2 be the linear path between (x_3, y_3) and (x_2, y_2). The linear path from the focus to the wave front is now

$$D_a = F + x_1 + L_1 + L_2 + (x_4 - x_2) \qquad (139)$$

but the optical path is longer by the introduction of the factor n

$$P_a = F + x_1 + n\,(L_1 + L_2) + (x_4 - x_2) \qquad (140)$$

By the conditions of parallel projection, we must have

$$P_a = P_0 \qquad (141)$$

and therefore

$$F + x_1 + n\,(L_1 + L_2) + (x_4 - x_2) = F + 2n\,T_0 + x_4$$

or

$$n\,(L_1 + L_2) + x_1 - x_2 = 2n\,T_0 \qquad (142)$$

and when the point (x_3, y_3) is so selected that equation (142) is satisfied, then (x_3, y_3) is on the ideal or co-paraboloidal surface.

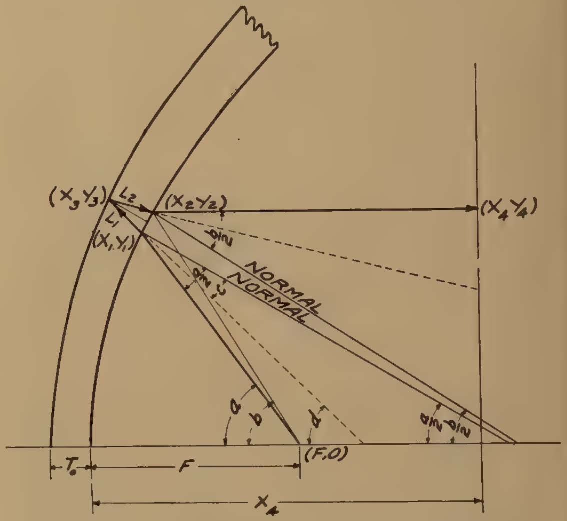


Fig. 138. The solution for the second surface of the mirror depends upon all light emitted at a given moment by the source at the focus reaching the plane at x_4 at the same time. The heavy lines show the path of a single ray to the plane at x_4

The mathematical work of solving these equations is of a simple nature, involving nothing more complicated than the finding of the directions and intersections of various straight lines, but if any high degree of accuracy is desired the work becomes quite extended. From the form of the equation it is seen that no direct solution is offered, and it thus represents a process rather than a solution. The steps in the process may be outlined as follows:

1. (1) Select some ray making an angle a with the axis
2. (2) Solve for its intersecting point (x_1, y_1) at the first surface
3. (3) Trace the ray into the glass and extend the path indefinitely
4. (4) Assume the angle b at point (x_2, y_2) of emergence

(5) Trace this assumed ray back along its path in the glass

(6) Find the crossing point of the selected ray and the assumed ray

(7) Find values L_1 and L_2 and substitute in equation (142) for the path length

(8) By noting the direction and size of the variation from the constant $2n\ T_0$ a second value of b can be assumed that will perhaps lead to a better approximation. A third or fourth value will usually come within the desired limits of accuracy.

In assuming values of the angle b it is a great help to plot the difference $b-a$ found at preceding points, and by drawing a curve through these points gain a fairly accurate value for the next one. This was done for one particular mirror of thickness, $T_0 = 0.0382369\,F$, giving the curve shown in Fig. 139. The angular space between the point of entrance and exit reaches a maximum of 1 deg. 4 min. at about 66 deg. from the axis of the mirror, but the linear distance between these two points increases indefinitely with the angle a, and does not reach a maximum and then diminish as does the angle $b-a$. It has been found that the difference $b-a$ varies almost directly as the value of T_0, so that a mirror of double thickness will have almost exactly a double value for the angular difference $b-a$. The curve of Fig. 139 may therefore be applied, after correcting for change of thickness, to any mirror of index 1.52.

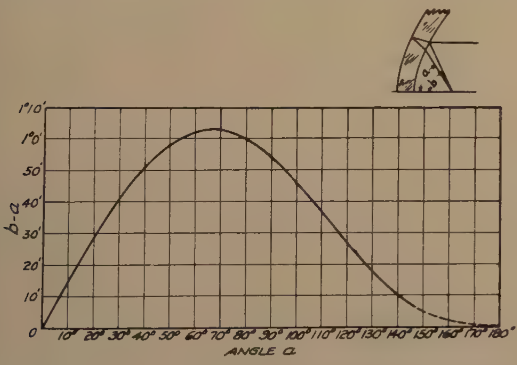


Fig. 139. Part of the preliminary work of computing the second surface is making an estimate of the angular difference between the points of entrance and exit for a given ray. This curve helps in making this estimate for a particular mirror

Thickness of Glass at Various Angles

The manner in which the thickness of the mirror increases from the center outward is illustrated by the curve in Fig. 140. The standard 60-deg. mirror is over 7 per cent thicker at the edge than at the center, while a deep mirror of 120 deg. such as is used for automobile headlights is 22 per cent thicker.

One of the simplest tests that can be made on a finished mirror is the measurement of the thickness of the glass. It is of course possible for a mirror to have two wholly incorrect surfaces and still have the proper thickness at all points, and the thickness test is therefore not positive in nature. With correct thickness at the various positions the mirror may be correct in the curvature of both the faces, but if the thickness is not as shown in Fig. 140 we may then be sure that one or both faces are incorrect.

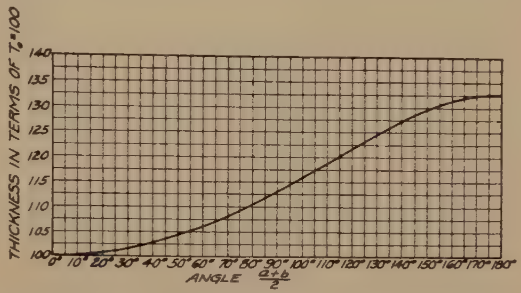


Fig. 140. The two surfaces of a parabolic mirror do not run parallel. There is a gradual increase in thickness from the center outward as shown by this curve. There is a definite limit to the thickness of a mirror of infinite extent; in the present case this limit is one-third greater than the central thickness

It is a matter of some difficulty to determine the angular position of points on the first surface, but the linear distance from the center may be readily measured with a flexible steel tape. The length of a meridian line in the surface to any desired radius y is, when measured on the paraboloidal face,

$$L = \frac{y}{4F}\sqrt{4F^2 + y^2} + 2.303\,F \log \frac{y + \sqrt{4F^2 + y^2}}{2F} \tag{143}$$

where the logarithm is in the common system to the base 10.

A Short Method for Computing the Co-paraboloid

In designing a templet for say a 60-in. mirror with a co-paraboloidal second surface it might be desirable or even necessary to compute points every half inch. The amount of work involved would in this case be a serious expense, and therefore means for shortening the computations have been sought. It is always desirable to base any mathematical short cut on some actual physical property of the article in question rather than resort to a purely empirical equation that will in all probability be limited in use to the range actually explored. Equations (150) and (151) are derived from certain mathematical relations between the paraboloid and its co-paraboloid, and at two points at least on any mirror of infinite extent the results are exact. At points between, there are errors which will be investigated later.

Let us consider a mirror to be made of extreme depth along the axis, so that the outer zone is nearly cylindrical in form, or mathematically having an infinite x co-ordinate. In Fig. 141 an element of the mirror is represented as having straight parallel surfaces, which of course would be true in the limiting case assumed. The entering ray and the reflected ray approach parallelism, but in the diagram they have been drawn at a considerable angle to one another for the sake of clearness.

With equal angle of incidence and emergence at (x_1, y_1) and (x_2, y_2), the angles of refraction c must also be equal at the two points. The triangle (x_1, y_1), (x_3, y_3), (x_2, y_2) is therefore isosceles.

Measuring from (x_1, y_1) to (x_3, y_3) the optical length of the path is

$$L_1 = \frac{n\,T}{\cos c} \qquad (144)$$

and, the triangle being isosceles

$$L_2 = \frac{n\,T}{\cos c} \qquad (145)$$

The base of the triangle has a length

$$B = 2\,T \tan c \qquad (146)$$

and from the construction of the diagram

$$x_2 - x_1 = 2\,T \tan c \sin \tfrac{1}{2}a. \qquad (147)$$

Substituting these values in equation (142) we get

$$2n\,T_0 = \frac{2\,T}{\cos c}(n - \sin c \sin \tfrac{1}{2}a) \qquad (148)$$

But, by Snell's law of refraction,

$$\sin \tfrac{1}{2}a = n \sin c \qquad (149)$$

and equation (148) becomes

$$2n\,T_0 = \frac{2\,T}{\cos c}(n - n \sin^2 c)$$

$$= \frac{2\,n\,T}{\cos c}(1 - \sin^2 c)$$

$$= 2\,n\,T \cos c$$

and finally

$$T = \frac{T_0}{\cos c}. \qquad (150)$$

This value for T is exact for $x =$ infinity (or $a = 180$ deg.) also for $x = 0$ (or $a = 0$ deg.) for in the latter case *cos c* is equal to unity.

Equation (150) although developed for a limiting condition has been found to be a very good approximation for all points between $a = 0$ and $a = 180$ deg. as is shown in Table XII. The computations are based on the angle a at which the light enters the glass, and equation (150) may therefore be written in a slightly more direct form:

$$T = \frac{T_0}{\sqrt{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2}} \qquad (151)$$

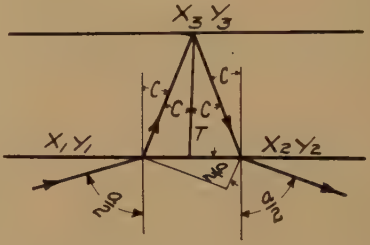


Fig. 141. The curvature of the first surface between the points of entrance and exit for a given ray becomes vanishingly small when the mirror angle a approaches 180 deg. The paraboloidal and co-paraboloidal surfaces become parallel and consideration of this fact leads to the greatly simplified "triangle" solution for the second surface

In the last column of Table XII the errors are given, the equal-path method being taken as correct and the differences are therefore the errors of the triangle method. The latter method is correct at 0 deg., somewhere between 20 deg. and 30 deg. where the errors go from plus to minus, again at 100 deg., and finally at 180 deg. With four points of zero error there is small possibility of serious errors at any point on a deep mirror. The maximum error in which we are interested is near 60 deg., and while this is about the worst possible point while the present standard of angular openings is retained, the error is not serious, being 1 part in 6000, which is well within the working limits.

The limiting thickness for a mirror of infinite depth ($x =$ infinity) is readily computed by equation (150), by making $a = 180$

deg. so that sin ½a equals unity. We have

$$T = \frac{T_0}{\sqrt{1-\left(\frac{1}{n}\right)^2}} \qquad (152)$$

and when $n=1.52$, T is equal to 1.328 T_0. The thickness of glass for this index therefore never exceeds by more than one-third the central thickness. This fact has a bearing on the attempt to find an equation for the outer curve. Two parabolas, even if nearly parallel near the apex, will diverge widely at large angles, say 140 deg; and for deep mirrors at least, the outer surface cannot be approximated by a paraboloidal form of equation. On the other hand, an outer surface parallel to the inner surface will err in making the glass too thin at all angles and will produce serious projection errors at even moderate values for the generating angle a. Therefore, the correct outer surface is neither parallel nor paraboloidal, but lies between these two extremes.

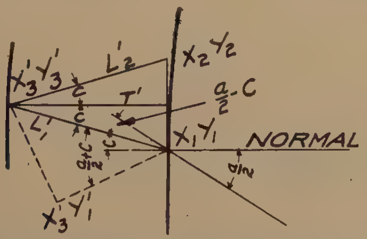


Fig. 142. The triangle of the "triangle" method represents a few of the physical facts accurately, but other dimensions, such as the path L_2', are grossly in error

Parametric Equations for Points on the Second Surface

The triangle of Fig. 142, which is the same as the triangle of Fig. 141, except that it is on a section of the mirror that has an appreciable curvature, is placed tangent to the first surface at (x_1, y_1). Let the length of the optical path from this point to the second surface be L_1', as distinguished from the real length L_1. Also let the point on the second surface at the end of L_1' be called (x_3', y_3') to distinguish it from (x_3, y_3). Also let T' be the height of the triangle, which is to take the place of the actual thickness T.

From Fig. 142 we can write

$$L_1' = \frac{T'}{\cos c} \qquad (153)$$

for according to the construction the height T' is parallel to the normal at (x_1, y_1). Let us assume that T' does not differ materially from T_1 then from (150) and (153) we can write

$$L_1' = \frac{T_0}{\cos^2 c} \qquad (154)$$

Again referring to Fig. 142, we have

$$x_1 - x_3' = L_1' \cos\left(\tfrac{1}{2}a + c\right) \qquad (155)$$

and

$$y_3' - y_1 = L_1' \sin\left(\tfrac{1}{2}a + c\right). \qquad (156)$$

In order to reduce these equations to forms having only one unknown, the following substitutions can be made.

$$\sin\left(\tfrac{1}{2}a + c\right) = \sin \tfrac{1}{2}a \cos c + \sin c \cos \tfrac{1}{2}a \qquad (157)$$

$$\cos\left(\tfrac{1}{2}a + c\right) = \cos \tfrac{1}{2}a \cos c - \sin \tfrac{1}{2}a \sin c \qquad (158)$$

TABLE XII

THICKNESS OF MIRROR

Points of Incidence at	$\frac{a+b}{2}$	(1) Thickness from Length of Bisector	(2) Thickness from Equations (150) or (151)	(2) − (1)
0°	0	0.0382369	0.0382369	0
10°	10° 7′ 25.56″	0.0383008	0.0383026	+0.0000018
20°	20° 14′ 25.52″	0.0384841	0.0384889	+0.0000048
30°	30° 20′ 35.93″	0.0388066	0.0388036	−0.0000030
40°	40° 25′ 36.00″	0.0392488	0.0392433	−0.0000055
50°	50° 29′ 9.40″	0.0398120	0.0398065	−0.0000055
60°	60° 31′ 5.64″	0.0404973	0.0404903	−0.0000070
80°	80° 29′ 58.67″	0.0422006	0.0421956	−0.0000050
100°	100° 23′ 13.77″	0.0442701	0.0442702	+0.0000001
120°	120° 13′ 41.42″	0.0465200	0.0465273	+0.0000073
140°	140° 5′ 13.485″	0.0486418	0.0486474	+0.0000056
180°	180° 0′ 0.000″	0.0507720	0.0507720	0.0000000

also

$$\sin c = \frac{1}{n} \sin \tfrac{1}{2}a \qquad (149)$$

$$\cos c = \sqrt{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2} \qquad (159)$$

and

$$x_1 = F \tan^2 \tfrac{1}{2}a \qquad (160)$$

$$y_1 = 2F \tan \tfrac{1}{2}a \qquad (58)$$

When these substitutions are made we find in equation (161):

$$x_3' = F \tan^2 \tfrac{1}{2}a - \frac{T_0}{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2} \left[\cos \tfrac{1}{2}a \sqrt{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2} - \frac{1}{n} \sin^2 \tfrac{1}{2}a\right] \qquad (161)$$

and in equation (162):

$$y_3' = 2F \tan \tfrac{1}{2}a + \frac{T_0}{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2} \left[\sin \tfrac{1}{2}a \sqrt{1 - \left(\frac{\sin \frac{1}{2}a}{n}\right)^2} + \frac{1}{2n} \sin a\right] \qquad (162)$$

In spite of the length of these equations the solution for points on the second surface is greatly simplified by their use. Not only is a single solution much shorter for (x_3', y_3') than for (x_3, y_3), but a single solution suffices where formerly it was only by good luck that the third or fourth trial gave good results. Table XIII illustrates the differences between x_3 and x_3' and between y_3 and y_3'.

In Fig. 143 a section of the mirror at $a = 50$ deg. is shown to a greatly enlarged scale; the solid lines show the exact relations and the dotted lines show the relation indicated by the "triangle" solution. The following comments apply to this particular point on the mirror:

(1) The triangle solution gives the path of the entering ray correctly

(2) The triangle solution gives the apex at (x_3', y_3') fairly close to the desired point (x_3, y_3)

(3) The height of the triangle is nearly equal to the thickness of the mirror

(4) The reflected ray from (x_3', y_3') is in error by nearly 1 deg. in the triangle solution

(5) The refracted ray at (x_2', y_2') is in error by over 1 deg. 30 min. in the triangle solution.

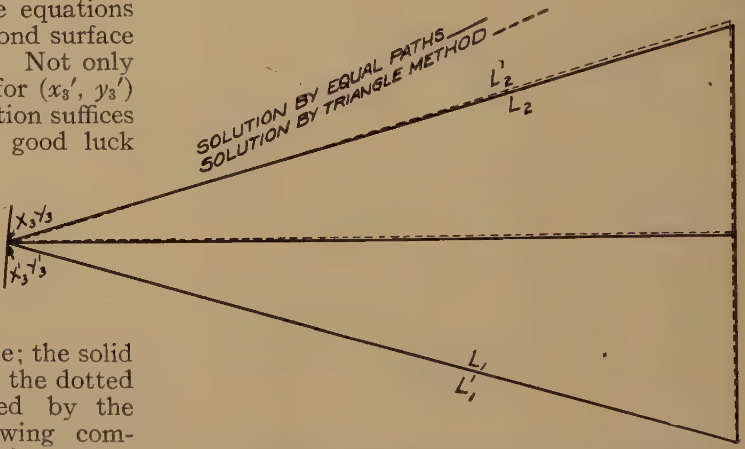


Fig 143. In this illustration the solid lines L_1 and L_2 indicate the actual path to the mirror, while L_1' and L_2', shown dotted, are the paths by the triangle solution. This drawing, which is to exact scale and greatly enlarged, shows how the triangle solution agrees with the exact solution in certain respects and disagrees in others

TABLE XIII

COMPARISON OF EQUAL-PATH AND TRIANGLE METHODS

Computed Points (x_3, y_3) and (x_3', y_3')

a	x_3	x_3'	y_3	y_3'
0°	−0.0382369	−0.0382369	0	0
10°	−0.0303077	−0.0303082	0.1805068	0.1805067
20°	−0.0060410	−0.0060443	0.3636953	0.3636700
30°	+0.0360576	+0.0360518	0.5524151	0.5524181
40°	+0.0987078	+0.0986974	0.7498718	0.7498786
50°	+0.1862497	+0.1862354	0.9598681	0.9598809
60°	+0.3053371	+0.3053198	1.1871401	1.1871602

The triangle method is thus not suited for tracing a ray completely through its optical path, but it is of great value in determining points on the second surface.

Mirror with Different Central Thickness T_0

There are two variables that have so far not been considered in the derivation of formulas or in the computations. One is the central thickness, which has been used as fixed datum point, and the other is the refractive index n. In practice T_0 varies from $0.02F$ to $0.05F$ and the refractive index n possibly varies from 1.515 to 1.525.

In order to see if variations in T_0 led to any great variation in the relation between T_0 and T, several 60-deg. points were computed by the two methods using values of T_0 ranging from $0.018F$ to $0.075F$. The 60-deg. point was selected as being one of the most difficult to satisfy. If the triangle method holds at 60 deg. we may feel satisfied with the results at other angles. The results of this computation are given in Table XIV where the greatest error in the value of T at 60 deg. is 1 part in 3000, which is far less than the normal manufacturing variations. The triangle method is therefore suitable for the computation of practically the entire series of parabolic mirrors in common use today. The only possible exception is found in certain small deep mirrors where the central thickness is 30 per cent of the focal length. As a rule these mirrors are of low optical accuracy, and although the triangle method may here give rather large systematic errors, still by its use the design would be a great improvement over present practice.

TABLE XIV

Central Thickness	CALCULATED THICKNESS AT $a=60°$	
	By Equal Paths	By Triangle
$T_0=0$	$1.058930\ T_0$	$1.058930\ T_0$
$T_0=0.018324\ F$	$1.059021\ T_0$	$1.058930\ T_0$
$T_0=0.0382369\ F$	$1.059106\ T_0$	$1.058930\ T_0$
$T_0=0.0556572\ F$	$1.059177\ T_0$	$1.058930\ T_0$
$T_0=0.0745035\ F$	$1.059255\ T_0$	$1.058930\ T_0$

Effect of Change in the Refractive Index

The refractive index of glass is different for the various wavelengths of the visible spectrum, and it also varies slightly in different batches of glass. Suppose that in a mirror designed for $n=1.52$ the index is actually 1.53. What is the effect on the action of the mirror? Substituting $n=1.53$ in equation (149) the thickness at $a=60$ deg. is found to be $1.058096\ T_0$, or 1 part in 1000 less than when $n=1.52$. It therefore is evident that the normal variations in the index, which are less than that just assumed, will not have any important influence on the action of a mirror designed for an average index such as is used in these computations.

(To be continued)

PREVIOUS INSTALLMENTS OF THIS SERIES OF ARTICLES

PART I. Types of Light Sources and Analysis of Paraboloidal Reflecting Surface by Meridian and Sagittal Lines (*February, 1923, p. 75*).

PART II. Parabolic Cylinder and Ellipsoidal Reflectors (*March, 1923, p. 160*).

PARTS III and IV. Characteristics of a Parabolic Mirror and Spherical Source of Light (*April and May, 1923, pp. 230 and 280*).

PART V. Methods of Computing Floodlighting. (*August, 1923, p. 575*).

PARTS VI, VII and VIII. The Parabolic Mirror and Disk Source of Light (*September, November and December, 1923, pp. 624, 780 and 818*).

PARTS IX and X. The High-intensity Arc and the Parabolic Mirror (*March and April, 1924, pp. 199 and 252*).

PART XI. Energy and Light Analysis of Arc and Incandescent Searchlights (*August, 1924, p. 504*).

The Diesel-electric Ship *"La Playa"*

By T. H. Relton

Publication Bureau, British Thomson-Houston Company

Electric drive has "made good" in the propulsion of ships. Both direct-current and alternating-current equipments have been placed in successful operation, some of the latter employing induction motors and others synchronous motors. The installations have included prime movers of the turbine type and also the internal combustion type. The best combination of these components for a given ship depends wholly upon the design of the ship and service in which it is to operate. A Diesel-electric direct-current propulsion equipment, as built for the fruit carrier *La Playa*, is described in the following article.—Editor.

The successful performance of the turbine-electric ship *San Benito** influenced the owners, the United Fruit Company, to place contracts for three more electrically propelled ships, the prime movers in this case being internal combustion engines.

The first of these three vessels, *La Playa*, illustrated in Fig. 1, was completed at Birkenhead several months ago and is of the following dimensions:

Length between perpendiculars	325 ft.
Breadth, moulded	48 ft.
Depth to upper deck	31 ft. 9 in.
Gross tonnage	3830
Speed	about 14 knots

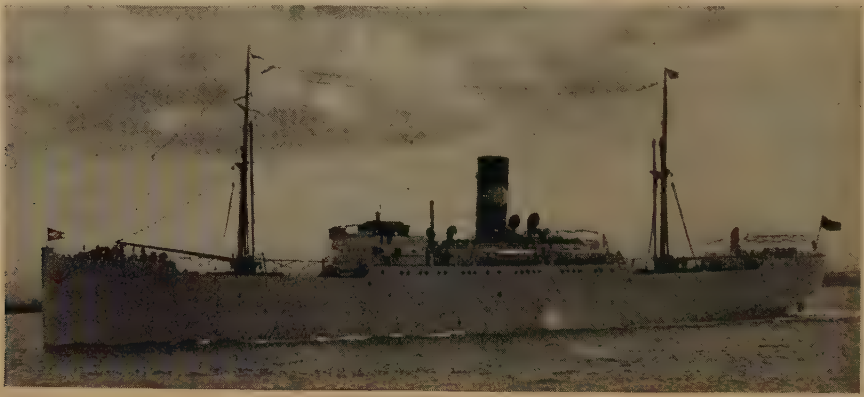


Fig. 1. ***La Playa*, First of a Fleet of Three Ships of the Diesel-electric Propulsion Type for the United Fruit Company**

Built specially for the carriage of bananas in tropical zones, all her holds are insulated with cork and are cooled by the cold air system. The vessel has a poop, bridge, and forecastle, a cruiser stern, a straight stem, two pole masts, and a single funnel. The double bottom is arranged for oil fuel and water ballast; the peaks are also arranged to carry water ballast.

There are three sister ships to the *San Benito*, and these are propelled by triple-expansion engines, so that when the Birkenhead contract is fulfilled the United Fruit Company will have seven vessels somewhat similar as regards size, three driven by steam reciprocating engines, one having steam turbines operating generators for the electric motors, and three of the Diesel-electric type.

Main Propelling Machinery

The machinery consists of four generating sets arranged in an engine room amidships which, in effect, forms a power station. Each unit consists of a four-cylinder Diesel engine developing 825 b.h.p. at 250 r.p.m. and directly coupled to a 500-kw. generator, shown in Fig. 2, supplying continuous current for propulsion purposes at 220 volts. The main generators are electrically coupled in series; and although all four generators are in operation at full power, three, two, or only one set may be used at reduced power if desired, the combined voltages being 880, 660, 440, or 220, according to the number of sets on the propelling circuits.

Main Propelling Motor

The main propelling twin motor, Fig. 3, is installed in a separate motor room right aft in the ship, thereby eliminating the usual shaft tunnel and resulting in a clear after hold for the carriage of fruit. The motor is rated 2500 b.h.p. at 95 r.p.m., with a temperature rise which will insure safety to the insulation when operating continuously at full power in the tropics. It comprises two units each complete with a separate magnet frame, armature, and commutator. The two armatures, Fig. 4, are electrically connected in series and are mounted on a common shaft supported between two pedestal bearings. As the propeller motor consists virtually of two motors in series it is possible to develop power for about three-quarter speed with only one-half of the motor available, should a breakdown occur to the other half.

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*Equipped with propulsion apparatus by the British Thomson-Houston Company.

Electrical Control Equipment and Operation

The control arrangements are such that the main propelling circuits are never interrupted and all regulation and reversing is carried out by varying the field circuits only. Provision is made however for isolating any of the generating units as may be desired. The control is carried out by means of a lever attached to a small controller fixed to the front of a sheet steel panel carrying the necessary instruments. This lever moves in a fore and aft direction on either side of a central stop point, and all the operator has to do when maneuvering is to move the lever onto the point required either ahead or astern. Fig. 5 shows the wiring diagram for this equipment.

The actual varying of the propelling generator fields during maneuvering is effected by means of a reversing potentiometer rheostat in each generator field circuit, and all the rheostats are simultaneously operated through gearing by a small electric motor. A movement of the control lever merely switches this small motor into circuit, and by means of the follow-up gear the small motor switches itself out and stops when it has moved the field rheostats to a position where a field strength is obtained on the generators corresponding to the speed point where the lever is at rest on the controller. In addition, a special type of overload current relay is placed in the main circuit; and this is arranged so that, should the operator attempt to accelerate or decelerate too quickly and so cause an excessive power current to flow in the system, the relay interrupts the supply to the small rheostat motor; and although the lever may be operated quickly the varying of the generator field strength is carried out only when the relay again completes the supply circuit to the small motor. This allows the operator to carry out orders in the quickest possible manner and safeguards the equipment against careless handling.

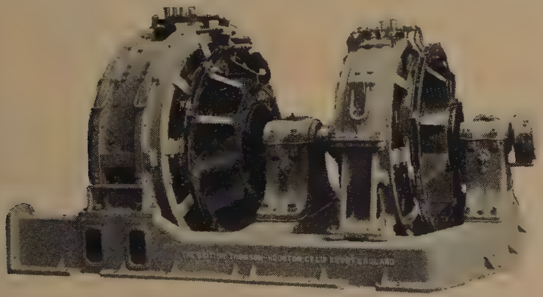

Fig. 2. One of the Four 500-kw. Main Generators and Auxiliary Generators. The main generators are connected in series electrically, each supplying continuous current at 220 volts to the main propulsion motor

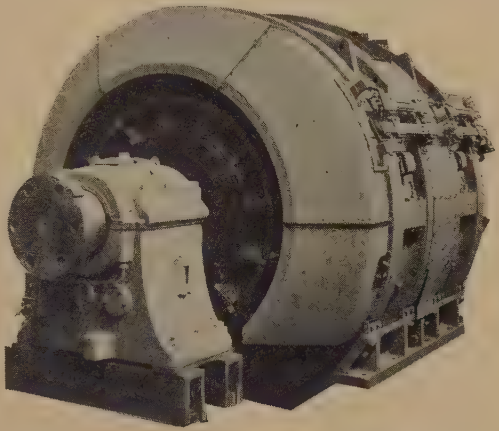

Fig. 3. Main-propulsion Twin Motor Rated 2500 b.h.p. at 95 r.p.m.

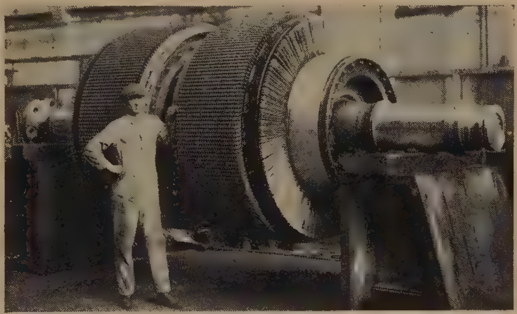

Fig. 4. Double Armature Mounted on a Single Shaft for Direct Connection to Propeller Shaft

Main circuit breakers or main power interrupting devices are not provided in the propelling circuit, as it is considered preferable in plants of this description to leave the stressing of the equipment under abnormal conditions entirely at the discretion of the engineer on watch.

In connection with this point it is well to bear in mind that the motor is on a circuit entirely different from the usual power circuit on land. This propeller motor is of a size which is equal in capacity to the generating plant, and in consequence is not so liable to prolonged overloads.

Also a ship requires considerable power to bring it to rest quickly, and this is altogether different from conditions obtaining in electric traction, where, for instance, it is so easy to arrange if necessary for an interruption of the power supply to bring the train quickly to a standstill.

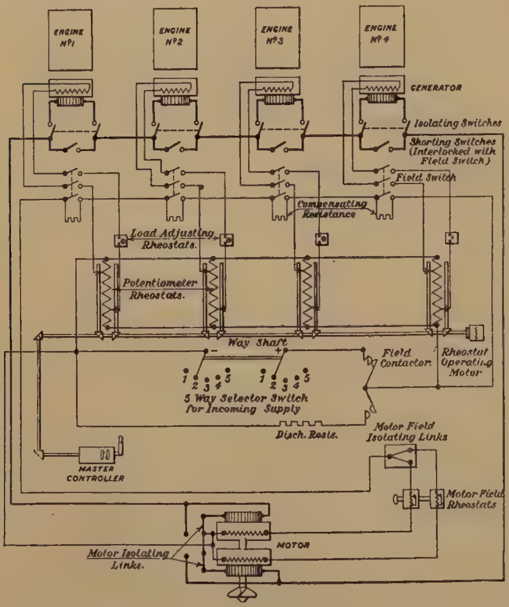

Fig. 5. Wiring Diagram, Showing Method of Control and Means for Isolating Certain Parts of Equipment

Normally the propelling system is connected through a circuit breaker and current limiting resistance to the ship's structure at the point between the two motor armatures. If an accidental ground occurs on any part of the main circuit which will open this circuit breaker, a loud ringing bell in the engine room gives audible warning.

The excitation supply is also without any automatic circuit breakers or fuses. The whole of the excitation is taken from a common source, and an overload relay causes the warning bell to ring if this circuit is overloaded due to a short circuit.

The instrument panel, illustrated in Fig. 6, is provided with an electric propeller-speed indicator showing the revolutions per minute, ahead and astern, and one indicating wattmeter for each engine set, showing the sum of the auxiliary and propelling loads in kilowatts and enabling the operator to see at a glance the load conditions on each engine without having to calculate them from the volt and ampere readings of the two generators. Adjacent to each of these wattmeters is a handwheel by means of which the field of each of the propelling generators can be adjusted, and that particular propelling generator's contribution to the propelling power circuit varied so as to maintain a full load on the engine. It also enables any particular engine load to be conveniently reduced, if this is desired due to a minor engine defect which is not important enough to warrant a complete stoppage.

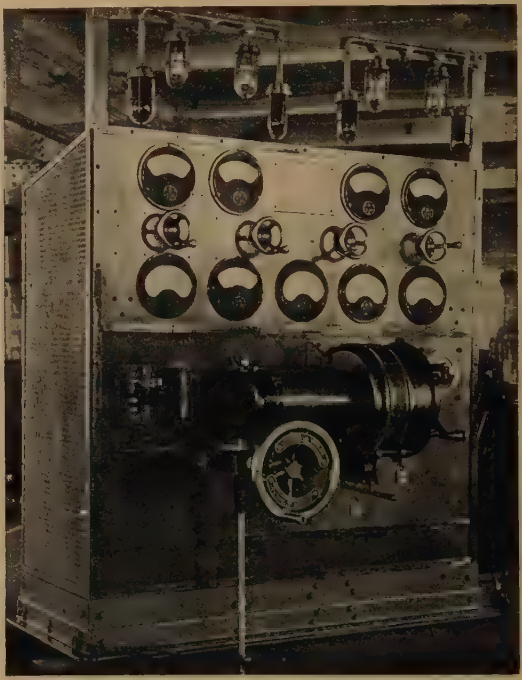

Fig. 6. Control and Instrument Panel for the Propulsion Equipment

A voltmeter with a six-point switch is provided to enable the operator to read the voltage of any of the four main generators, the motor voltage, and the exciter voltage. An ammeter is provided which indicates the propelling power current, this being the same current as is supplied by the generators in series. A wattmeter, calibrated also in electrical horse power, provides a convenient form of measuring the power developed by the motor without the operator requiring to make a mental calculation from the varying volts and amperes. The two last mentioned instruments are placed near the speed indicator, and a handwheel is conveniently placed alongside which operates a rheostat in the propelling motor field circuit and enables the motor field to be varied and the speed consequently adjusted to compensate for temperature variation or light draught conditions. This also enables the speed of the propeller to be easily adjusted so that when propelling the ship with a reduced number of engine sets the engine or engines, as the case may be, can be fully loaded.

When it is remembered that, with a low auxiliary load, four engines will give 95 propeller r.p.m., three engines 88 r.p.m., two engines 76 r.p.m., and one engine 63 r.p.m., the importance of this point will be readily seen.

The figures given are liable to be affected by such factors as draught and condition of the ship's hull, but results on trials have very closely confirmed them. When considering this particular feature of the equipment it should be noted that the consumption of fuel and lubricating oil per s.h.p. is exactly the same at all four speeds.

Another feature of the equipment is the simple manner in which a generating set can be put into or taken out of service without entailing a stoppage of the propeller motor. Even if the set which it is desired to shut down is supplying the excitation, the operator at the control panel can, by means of a convenient handwheel, transfer the excitation to another auxiliary generator without leaving his post.

Each propelling generator is provided with a protected type of switch panel carrying four operating handles and suitable interlocking gear which enable a generator to be put in the propelling circuit or taken out without damage by careless handling. These panels also allow any one of the propelling generators to be used for auxiliary load.

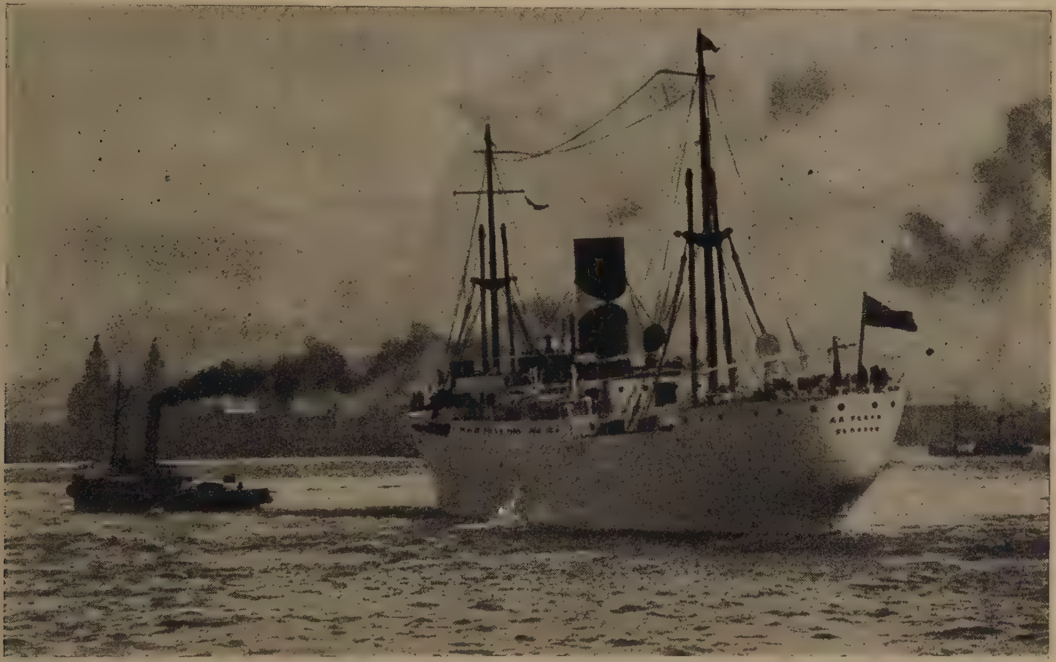

Fig. 7. Half-stern View of the Diesel-electric Driven Ship, *La Playa*

This last feature is very useful in port because it enables the refrigerating plant to be run at its full capacity if necessary, and also provides ample power for operating the cargo winches which are especially arranged with a view to handling the cargo in the minimum time in port.

From the foregoing description it will be seen that everything is so arranged that it is a comparatively simple matter to keep a unity load-factor on every engine when it is operating.

At the commencement of a trip with a cargo on board the refrigerating load (approximately 500 h.p. total) will be requiring its maximum power supply, and the various capacities of the individual electrical units have been so proportioned that when this load is at its minimum the propelling portion of the equipment can absorb all the remainder of the output of the four engines.

In addition to paying special attention to providing simple means whereby maximum economy in fuel consumption can be obtained at widely different powers and sea speeds, the arrangement of the equipment was made to take full advantage of the multiple unit system in the case of failure of any portion of the power installation. As already mentioned, each propelling generator is provided with an isolating switch panel enabling any unit to be taken out of circuit as desired.

Each unit is also provided with its own field regulating rheostat so that a defect in a rheostat can be repaired at sea, if necessary, without entailing a stoppage of the propelling motor. This also applies to the two separate motor field systems.

The propeller motor, consisting virtually of two motors in series, also allows of one motor being available and capable of about three-fourths speed in case of break down occurring to the other.

As a precaution against failure of the small rheostat operating motor which might conceivably fail when maneuvering the vessel in narrow waters, a handwheel placed close to the control lever enables the propelling generator field rheostats to be manually operated. This handwheel is normally disengaged from the rheostat operating shaft, but is always ready for instant engagement should the propeller speed fail to respond to a movement of the control lever and, when engaged, it automatically cuts the small rheostat motor out of circuit. The control lever is so arranged as to allow a complete full power reversal to be carried out in about eight seconds. The effort required to do this manually is too great to allow it to be done in this period, and the handwheel is geared so that it can be operated conveniently through a full power reversal in about thirty seconds.

When bringing the propeller to rest prior to a reversal in its direction of rotation, the power returned to the electrical system due to the action of the water causing the propeller to keep rotating in a forward direction (and which in turn drives the propeller motor as a generator) is dissipated in motoring the propelling generators.

The propelling generators in turn partially or entirely supply the motive power to rotate the engines and auxiliary generators and, due to the considerable amount of power required to overcome the friction load of a Diesel engine at full speed (about 33 per cent of its normal output), this forms a very convenient form of dissipating the braking energy.

In order to prevent the operator from slowing the propeller motor too suddenly by means of the automatic control, a safeguard in the form of a limit switch is fitted to each engine. These limit switches control the supply to the small rheostat operating motor in such a way as to prevent any racing of the engines and to allow the auxiliary generators to do their share in absorbing the braking energy.

Special Features of Arrangement

Special attention had to be given to a provision for carrying out repairs to the electrical equipment. On a ship of this description, and as a matter of fact on most ships, the electrical engineer has a much more difficult problem to contend with than on land. The machinery has to be very closely built into the vessel, and space for access (in case it is necessary to carry out repairs) has to be cut down to the very minimum. Also it is extremely important that repairs be made in the minimum time in view of the heavy harbor and dock dues charged on the vessel when in port in addition to the losses incurred directly as a result of the hold-up.

The motor and propelling generator magnet frames are made cylindrical and fitted into special cradles which allow the frame to be rotated so as to allow of the lower magnet coils being taken out, if necessary, without removing the armatures. This arrangement was necessary in order to get the shaft centers as low as possible, and therefore it was not necessary to provide any clearance between the bottom of the magnet frames and the ship's structure to allow of the bolts being withdrawn before the pole pieces could be removed. This makes all the field coils accessible without disturbing any armatures.

A very limited amount of head room only is available but if all the magnet poles are removed from the bottom halves of the magnet frames sufficient space can be obtained for the top half so as to enable armature winding repairs to be carried out in position.

This arrangement is particularly necessary in the case of the propelling motor, as otherwise it would be necessary to open up the ship's structure to get the armature out of the vessel.

Provisions for Routine Testing

Special provision is also made to enable the insulation of the whole of the propelling equipment to be quickly and conveniently tested in sections when in port so that the readings can be logged at regular periods and in this way defects located before an actual stoppage occurs.

For use during a voyage a leakage current indicator is provided and readings are taken once every watch. In order to obtain these readings the engineer who visits the motor room momentarily opens the earth circuit breaker. This in turn causes the warning bell to operate in the engine room, which besides indicating that the bell is in order also serves to warn everybody that they are liable to an 880-volt shock if they touch any of the live parts of the main propelling circuit.

In connection with this point, the whole of the propelling equipment is so conservatively rated that strict instructions are given that no commutator adjustment or cleaning has to be carried out without first of all isolating the machine from the propelling circuit.

Performance

During the trials the electrical machinery gave very promising results, and because of the very liberal rating there was absolutely no suggestion of any "nursing" being required during the whole period. It was only occasionally that the motor room was visited specially to observe the performance of the motor, and in normal service the practice will be to visit it once a watch to take a reading of the revolution counter and have a general look at the mechanical gear such as the thrust block.

The whole of the electrical propulsion equipment, generators, propeller motors, and control gear have been built and supplied by the British Thomson-Houston Co.

Notes on the Testing and Installation of Edison Bipolar Dynamos: 1880-1886

By W. S. Andrews

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Great credit is due the pioneers for their work in the development of electrical apparatus from 1880 to 1886, hampered as they were by the lack of adequate testing instruments. The need for ready and accurate means of measuring voltage, current, and power led to the invention of many devices that in the light of present equipment seem crude. In this brief historical review the author chronicles the development of testing equipment at the Edison Machine Works in New York City. A description of the first Edison three-wire central station, located at Sunbury, Pa., forms an interesting sidelight on operating conditions forty-one years ago. Mr. Edison read this article in manuscript and heartily approved its publication.—Editor.

Hundreds of Edison bipolar dynamos were made during the period from 1880 to 1886 at Menlo Park, N. J., and at the Edison Machine Works in New York City, but the facilities and methods for testing them were almost incredibly crude as compared with the refinements of more modern practice.

The only instruments of precision which were then available, and which indeed have not since been greatly improved, were the Thomson reflecting galvanometer and the Wheatstone bridge. Voltmeters, ammeters, and wattmeters, as now so commonly used, had not been developed, and the measurement of voltage was based on the so-called "Standard Battery." A cell of this battery consisted of a strip of copper immersed in a saturated solution of chemically pure copper sulphate in distilled water, contained in a porous cell, and an amalgamated strip of zinc in a saturated solution of chemically pure zinc sulphate in distilled water in the outer vessel. When freshly made, and in good condition, this cell was rated at 1.079 volts. A battery of 50 cells was kept constantly on hand and tested frequently for depreciation, as it provided the only standard for reading the voltage of dynamos in operation. These 50 cells connected in series produced approximately 54 volts. For testing purposes, they were connected to a Thomson reflecting galvanometer through a variable high resistance of about 100,000 ohms. The resistance was then regulated to get a deflection of 54 divisions on the galvanometer scale, making each division equal to one volt. Then, without changing the resistance, the galvanometer was switched onto the dynamo leads and the voltage read. To insure the delicate galvanometer against stray magnetism, it was surrounded by an open cylinder of cast iron about an inch thick, a suitable hole being made for the passage of the light ray.

The electrical testing of a dynamo consisted in first measuring the resistance of its field magnet, and seeing that the winding was well insulated. The resistance of the armature winding was then measured all around between opposite commutator bars, and its insulation from its base was also measured. If these readings were satisfactory, the armature was put in place, and the dynamo set up for a running test which consisted in operating the machine on a full load of lamps at normal voltage for two or three hours. No exact rise in temperature was given as allowable, but if the shellac insulating varnish did not smoke, and if no *hot spots* developed that could be detected by the hand, the dynamo was judged to be electrically acceptable.

The unit of current at that time (1880-1884) was termed the "weber." After that, the name was changed to "ampere." At about this date, the unit of electrical power was a "volt-ampere," and afterwards, in about 1889-1890, it was renamed the "watt."

The Edison bipolar dynamos, however, at this early period were standardized according to the number of 16 candle-power lamps they could carry without overheating.

TABLE I

EDISON CARBON FILAMENT LAMPS MADE IN 1883

Type	Candle-Power	Ohms Hot	Webers	Volts	Lamps Per H.P.
A	32	86	1.18	102	6.19
A	16	137	0.745	102	9.8
A	16	140	0.747	105	9.5
A	16	121	0.828	100	9.0
A	16	103	0.92	95	8.5
A	10	208	0.49	102	14.88
B	8	69	0.745	51	19.61
B	16	42	1.2	51	12.15

In this connection, Table I shows some historically interesting factors regarding the lamps manufactured by the Edison Lamp Factory at Harrison, N. J., in 1883.

The only instrument in the testing room of the Edison Machine Works by which voltage could be measured directly was an ancient Deprèz galvanometer which was little used, because of its cumbersome weight and its liability to get out of order and show incorrect readings. As previously stated, it was therefore the general practice to determine voltage by the reflecting galvanometer and standard battery.

At this time also (1880-1884) the measurement of "webers" was effected by passing the current through a strip of German silver of known resistance, and measuring the drop in voltage across the ends of the strip by the reflecting galvanometer. The "webers" were then calculated by Ohm's law. To save time, the galvanometer was usually adjusted so that the scale divisions indicated "webers" directly.

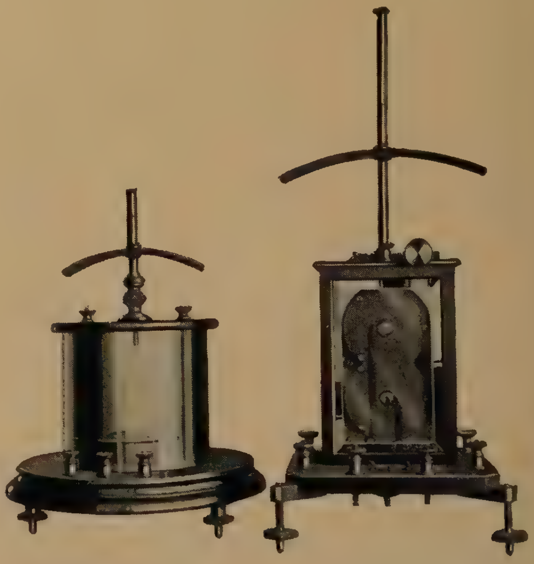

Fig. 1. Astatic Galvanometer (*Left*); and Thomson Reflecting Galvanometer (*Right*)

To facilitate the testing of dynamos of various sizes, a number of sheets of German silver of different carrying capacities and resistance were secured in a wooden box. One end of each sheet was connected to a common terminal of heavy copper, the other end being connected to another copper terminal through a plug switch, thus permitting the resistances to be used individually or in any desired multiple arrangement to meet requirements. About 1000 incandescent lamps were wired up in suitable groups along the rafters and on the side walls of the testing room to provide load for the dynamos. These lamps were mostly faulty in some way, so as to be unfit for sale, but just as good as perfect lamps for the purpose of load.

Commercial incandescent lamps were tested for candle-power at different voltages by a Bunsen photometer, set up in a dark room devoted to its use, the "Standard Candle," burning 120 grains of paraffin per hour, being used for comparison with the lamp.

A lamp socket was usually located on the head board of dynamos and the brightness of this "pilot lamp" was often the only guide for operating the dynamo at proper voltage. In view of all our existing refinements in measuring instruments, it seems almost incredible that any satisfactory results could attend such a method, yet it was practiced with more or less success in hundreds of small isolated plants at that time.

An advance in dynamo regulation was made by the introduction of the red and blue lamp voltage indicators. This device was simply a large double contact telegraph relay, the magnet of which was connected directly to the lighting circuit. The pivoted armature was balanced against the pull of the magnet, by an adjustable spring, so that at correct line voltage the contact arm floated between two contacts. If the line voltage rose above normal the armature was drawn toward the magnet, closing a circuit that lighted a red lamp. On the other hand, if the line voltage dropped below normal, the spring pulled back the relay armature, closing a circuit which lighted a blue lamp. In either case, the attention of the dynamo tender was called by the ringing of an electric bell, and it would be his duty to restore the voltage to normal by adjusting the field rheostat. Many ingenious applications of small supplementary springs, etc., were used in the endeavor to stabilize the sensitive balance of the relay armature, and keep it equally poised between the two contacts under insignificant variations of voltage, but in some cases it persisted in sticking to one or other of the contacts, and so keeping a red or a blue lamp lighted, and also the bell ringing continuously. Under these conditions it then became necessary to disconnect the instrument and regulate by the "pilot" lamp.

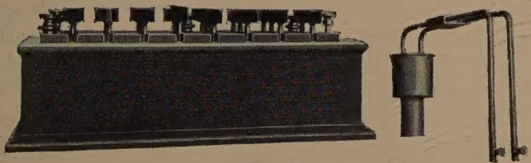

Fig. 2. Wheatstone Bridge (*Left*); and Standard Ohm Resistance (*Right*)

An expensive and rather complicated improvement on the foregoing device was termed the "Edison Automatic Voltage Regulator." In this apparatus, resistance was automatically cut in and out of the dynamo field magnet by a swinging arm actuated by two electro-magnets. These magnets were connected to the colored-lamp voltage regulator in the same way as the red and blue lamps, so that if the line voltage dropped below normal, the magnet on the blue side would cut resistance out of the field circuit, or in the reverse case, the magnet on the red side would cut in more resistance. Two dashpots filled with glycerine served to hinder the magnets from operating too quickly. Nevertheless it was often difficult to adjust the parts so as to prevent the "hunting" of the dynamo, that is, its tendency to swing backwards and forwards between extremes of high and low voltage. These automatic regulators were sold chiefly to large isolated plants in woolen mills, etc., but they were costly to purchase and erratic in operation. Mr. Edison would never permit their use in central stations, as he did not consider them sufficiently reliable for public service supply. In 1882 Mr. Edison invented the three-wire system of electrical distribution to reduce the large amount of copper required in the two-wire system, and he requested the writer to try out the scheme in a small way in the testing room of the Edison Machine Works. The results being quite satisfactory, arrangements were started to apply this new system to central station distribution. The Sunbury (Pa.) Electric Light, Heat & Power Company was organized, and the first Edison three-wire

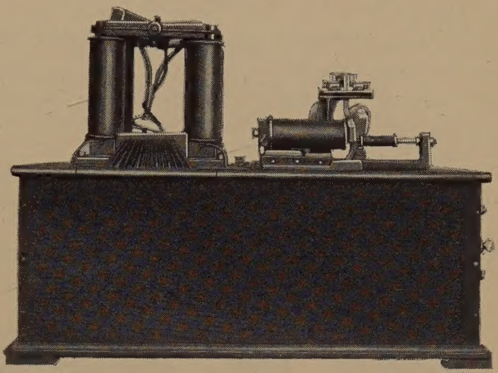

Fig. 3. Edison Automatic Voltage Regulator

central station was started there for commercial work on July 4, 1883, operating two "L" dynamos with a capacity of about 650 ten-candle-power incandescent lamps. The electrical distribution was a success from the start, and the great saving in copper conductors was then demonstrated beyond dispute.

The electrical equipment of this station was very simple, consisting only of the two field rheostats for controlling the dynamos, two voltage indicators, showing the pressure at the end of the three-wire feeder line, and an ammeter interpolated in the neutral feeder wire to show if a proper balance of lamp load was maintained. The feeder line was connected to the station "bus" through three plain plug switches. With this crude and meager apparatus the Sunbury Central Station was successfully operated for many years.

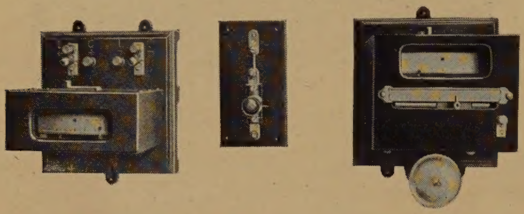

Fig. 4. Old Style Voltage Indicator (*Left*); Old Type Plug Switch (*Center*); and another Old Style Voltage Indicator (*Right*)

Although a little out of place in this article, it is interesting to record as a matter of history that these two dynamos, which were the first pair to be operated in a commercial Edison three-wire central station, gave regular service for 20 consecutive years after their installation in Sunbury, in 1883. They were then shipped, with their Armington and Sims engine, to the St. Louis Exposition in 1904, where they formed one of the main attractions in the "Edisonia" Exhibit. At the close of the Exposition, they were returned to Sunbury, used for a time as spare machines, and then put into storage. In 1922 they were rescued from oblivion, shipped to New York City, and after some minor repairs were set up for exhibition at the electrical show held in October at the Grand Central Palace in New York. They now hold a permanent and honorable place in the "Historical Collection of Old-time Dynamos and Electrical Apparatus" which is in process of formation in New York under the direction of its curator, Mr. F. A. Wardlaw, and the auspices of the Association of Edison Illuminating Companies and the Edison Pioneers.

The general public appreciation of the Edison incandescent lamp was now indicated by a constantly increasing demand, both in connection with central station installations and isolated plants. A little later on, this demand for "more light" had naturally to be met by the installation of additional dynamos. Troubles then began to multiply by the heating and destruction of armatures, when two or more dynamos were coupled in multiple, owing to the difficulty of dividing the total load evenly between them in the absence of any current indicators. This was a very serious situation, and after careful consideration by Mr. Edison, the writer was instructed to devise a cheap and rugged form of ampere meter, one of which could be connected in circuit with each dynamo to show its load. This decision led to the immediate development of the "pendulum" ammeter, the readings of which depended solely on the balance between electromagnetism and gravity—no adjusting springs being employed—and the use of these simple instruments immediately checked the armature casualties.

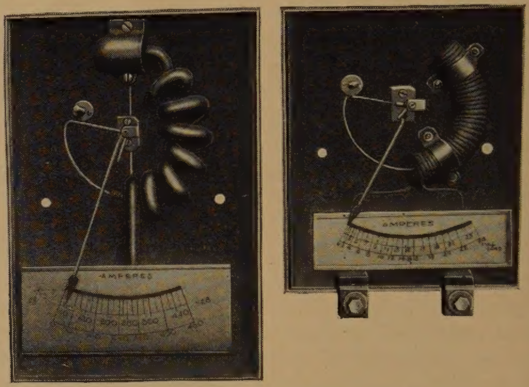

Fig. 5. Two Types of Pendulum Ammeters

By 1885-6 the various original forms of ammeters, voltmeters, switches, etc., had been so much modified and improved that previous difficulties were largely overcome, and from that time on the path of the electrical engineer was less thickly beset with the obstacles which had to be met and surmounted by the early pioneers.

LIBRARY SECTION

Condensed references to some of the more important articles in the technical press, as selected by the G-E Main Library, will be listed in this section each month. New books of interest to the industry will also be listed. In special cases, where copy of an article is wanted which cannot be obtained through regular channels or local libraries, we will suggest other sources on application.

Bearings

Sleeve Bearing Keeps Oil from Splattering Motor. Pruger, R.
Coal Age, June 26, 1924; v. 25, pp. 945-947.
(Describes a special motor bearing designed to prevent entrance of oil into the windings.)

Circuit Breakers

Explosion Pots. Garrard, Charles C.
Elec'n., June 20, 1924; v. 92, pp. 766-767.
(Short article on the use of explosion pots in oil circuit breakers.)

Corrosion

Paradox in Corrosion. Evans, Ulick R.
Chem. and Met. Engng., June 16, 1924; v. 30, pp. 949-953.
(Explains why corrosion due to oxidation is sometimes greatest where oxygen is excluded.)

Electric Cables

Beetles Attack Lead Cables and Interrupt Service. Winters, S. R.
Elec. Wld., June 28, 1924; v. 83, pp. 1337-1338.
(Short account of experiments by the U.S. Dept. of Agriculture to discover methods of combating the lead-cable boring beetle.)

Electric Control Systems

Supervising Systems for the Remote Control of Unattended Substations. Sarjeant, C. J. and Riley, T. N.
Elec. Rev., July 4, 1924; v. 95, pp. 8-9.

Electric Distribution

Rural Electric Service. Neff, G. C.
Elec. Lt. and Pr., June, 1924; v. 2, pp. 32-34, 72.
(Abstract of a National Electric Light Association report.)

Electric Furnaces

Electricity Versus Oil for Heating Iron Enameling Furnaces. Mulvaney, H. A.
Jour. Elec., June 15, 1924; v. 52, pp. 487-490.
(Gives some interesting comparisons in costs of operation and of results obtained in the use of electrically heated furnaces and oil-heated furnaces.)

Metallic Resistor in Industrial Heating Furnaces. Collins, E. F.
Chem. and Met. Engng., June 16, 1924; v. 30, pp. 936-941.
("The first of two articles dealing with the application and design of electrical heating equipment.")

Electric Lighting—Railroad Yards

Floodlighting Railroad Yards. McAllister, E. G.
Elec. Wld., June 28, 1924; v. 83, pp. 1329-1332.
(Methods used by the Norfolk & Western R. R.)

Electric Locomotives

Details of New Pennsylvania Electric Locomotives.
Elec. Rwy. Jour., June 7, 1924; v. 63, pp. 888-889.

Electric Motors, Synchronous

Synchronous Induction Motor. Cotton, H.
Wld. Power, June, 1924; v. 1, pp. 329-337.
(On the theory of operation. Serial.)

Electric Transmission

Interconnection Proposed for New England.
Power Pl. Engng., June 15, 1924; v. 28, pp. 653-655.
(A summary of the proposed plan.)

Electric Transmission Lines

Actual Costs of Transmission Line and Substation.
Elec. Wld., June 28, 1924; v. 83, pp. 1325-1327.
("Comprehensive data on recently completed 132-kv. system in Middle West.")

Feed Water Treatment

Prevention of Scale Formation by Boiler Water Conditioning. Hall, R. E. and others.
Iron and St. Engr., June, 1924; v. 1, pp. 312-327.

Heat Transmission

Research in Heat Transmission. Buckingham, Edgar.
Mech. Engng., July, 1924; v. 46, pp. 386-388.
(Short paper discussing methods and problems to be considered.)

Heating, Industrial

Mercury Vapor as an Industrial Heating Medium. Field, Crosby.
Chem. and Met. Engng., June 23, 1924; v. 30, pp. 987-991.
(Outlines this system and discusses various other sources of heat at high temperature.)

Hydro-electric Plants, Automatic

7300-kv-a. Automatic Hydro Station—I. Whitsit, L. A.
Elec. Wld., June 28, 1924; v. 83, pp. 1319-1322.
(Illustrates and describes the Sprite Creek plant of the Adirondack Power & Light Company near Little Falls, N. Y.)

Insulators

New 110,000-volt Suspension Insulator.
Elec. Wld., June 14, 1924; v. 83, pp. 1229-1230.
(A single-unit, suspension-type insulator of unusual design is described by Prof. H. B. Smith, before a meeting of the American Institute of Electrical Engineers.)

Laboratories

Laboratory for the Central Station. Morgan, John D.
Power Pl. Engng., June 15, 1924; v. 28, pp. 637-638.
(Points out the usefulness of such laboratories.)

Magnetic Separation

Magnetic Separation.
Elec. Rev., June 6, 1924; v. 94, pp. 910-911.
(Short article on magnetic separators for removing combustible matter from ash and for separating tramp iron from coal.)

Poles, Wooden

Determination of Pole Sizes. Mathews, J. Howard.
Elec. Wld., June 7, 1924; v. 83, pp. 1173-1176.
(Gives tables for calculating rapidly the pole size for any type of line. Based on National Electrical Safety Code.)

Power Plants, Electric

Illinois Mine Generates Own Power Cheaply. Allen, Andrews and Hebley, H. F.
Coal Age, July 3, 1924; v. 26, pp. 3-7.
(Describes a generating plant at No. 4 mine of the Donk Bros. Coal and Coke Company.)

Protective Apparatus

Rises in Pressure and Protection of Alternating-current Circuits. Partridge, G. W.
Elec. Rev., June 20, 1924; v. 94, pp. 992-994.

Radio Receivers

Story of the Super-Heterodyne. Armstrong, Edwin H.
Radio Broadcast, July, 1924; v. 5, pp. 198-207.
("Its origin, development and some recent improvements.")

Railroads—Electrification

Virginian Railway Electrification. Smith, Homer K.
Rwy. Age, June 7, 1924; v. 76, pp. 1353-1358.
("An outline of the conditions which caused the management to adopt electric traction." Same appears in *Railway Electrical Engineer* for June, 1924, pp. 169-174.)

Relays

Calibration of Induction-type Overload Relays. Andrews, R. A.
Elec. Wld., June 21, 1924; v. 83, pp. 1278-1280.
(An oscillographic study of electrical characteristics shows that iron saturation makes phantom testing unreliable. Numerous graphs are given.)

Relays

Generator-field Destroying and Restoring Device. Brown, Ralph.
Power, July 1, 1924; v. 60, p. 17.
(Describes a "field relay" protective device that is said to be useful for clearing certain kinds of faults in transmission systems.)

Resonance, Electric

Resonance on 30,000-volt Systems. Taylor, A. M.
Elec'n., June 6, 1924; v. 92, pp. 690-691.

Steam Turbines—Testing

Testing Steam Turbine and Barometric Condenser. Youtsey, Floyd S.
Power, June 17, 1924; v. 59, pp. 979-980.
(Brief article describing method of test and results obtained.)

NEW BOOKS

Choice of Switchgear for Main and Substations. W. A. Coates. 292 pp., 1924, N. Y., D. Van Nostrand Co.

Colliery Electrical Engineering. G. M. Harvey. 387 pp., 1924, N. Y., Isaac Pitman & Sons.

Conduit Wiring. Terrell Croft. 458 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.

Direct-current Dynamo and Motor Faults. R. M. Archer. 204 pp., 1924, N. Y., Isaac Pitman & Sons.

Electric Elevator Equipment for Modern Buildings. Ronald Grierson. 179 pp., 1924, N. Y., D. Van Nostrand Co.

Electrical Engineering Practice. Ed. 4, vol. 1. J. W. Meares and R. E. Neale. 584 pp., 1924, N. Y., John Wiley & Sons.

Electrical Measuring Instruments. Pt. 1: Commercial and Indicating Instruments. C. V. Drysdale and A. C. Jolley. 440 pp., 1924, Lond., Ernest Benn, Ltd.

Handbook of Telephone Circuit Diagrams with Explanations. John M. Heath. 279 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.

Marks' Mechanical Engineers' Handbook. Ed. 2. Lionel S. Marks, editor. 1986 pp., N. Y., McGraw-Hill Book Co., Inc.

Modern Theory and Practice of Pumping. Norman Swindin. 364 pp., 1924, Lond., Ernest Benn, Ltd.

Oil Engines. A. L. Bird. 281 pp., n. d., N. Y., E. P. Dutton & Co.

Power Station Efficiency Control. John Bruce. 244 pp., 1924, N. Y., Isaac Pitman & Sons.

Super-Power as an Aid to Progress. Guy E. Tripp. 61 pp., 1924, N. Y., G. P. Putman's Sons.

Supervision and Maintenance of Steam-raising Plant. Charles A. Suckan. 342 pp., 1924, N. Y., D. Van Nostrand Co.

Technical Organization, Its Development and Administration. John M. Weiss and Charles R. Downs. 197 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.